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Comparison of Different Regulations and Metaheuristic Algorithms in Beam Design

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Abstract

In this first study, the rectangular reinforced concrete beam's costs and cross-section sizes are found by using Harmony Search (HS), Differential Evolution Algorithm (DE), Jaya Algorithm, Teaching- Learning Based Algorithm (TLBO), Hybrid algorithm (Jaya-TLBO) and Flower Pollination Algorithm (FPA) separately by using ACI 318 building code. In addition, in order to better see how successful the algorithms are, the standard deviation of the algorithms used in the project in a certain number of iterations, price changes and in which iteration the minimum cost is compared. As a result of running different algorithms 5, 10, 15 and 20 times, separate values are recorded, and the average number of iterations of the algorithms for each is shown by finding the standard deviation values. Furthermore, Hybrid Algorithm reached the objective function in fewer iterations and their standard deviations reached 0 earlier. In the second study, the beam design is made according to the ACI 318, TS500 and Eurocode 2 regulations under certain loads by using a Hybrid Algorithm with different concrete classes. Optimization of this design is made using the Matlab program, and comparisons are made between regulations. Eurocode and TS500 design costs are roughly the same; however, ACI 318's design is the cheapest.

Keywords: Beam Design, Metaheuristic Algorithms, Building codes, Cost Optimization, Hybrid Algorithm.

1. Introduction

Over time, studies have been carried out in many areas around the world in order to apply sustainable and safe systems [1], and as a result, it has enabled some systems to be implemented, designed and made in a short time with different desired features according to restraints properties [2]. These have accelerated by spreading to many areas instead of being limited to only one area, and in the general sense of the recent studies, studies are carried out to use the world's resources more efficiently and by preventing their consumption, expense [3] and pollution [4]. While these studies are carried out under sustainability, designs have become the focal point of making this situation in the foreground. Increasingly complex problems are solved by metaheuristic algorithms easily and successfully [5] and enable to design of cost-effective structures [6].
Studies in the field of civil engineering have likewise gained momentum and in this process, many structures; design according to the type of use, the use of different materials and different systemic designs are provided. In different beam designs, section sizes and similar cases, the structure is selected and completed according to the purpose of use. However, in the design phase, the cross-section dimensions are assigned by the trial and error method, which is the traditional method, and analyses are made and the results are interpreted. However, such designs which have no optimal numerical solutions can prevent very effective results in terms of time and cost. By creating objective functions (cost, CO_2 emission which is prominent in

structural design [7], displacement, etc.), reaching the best results in a short time is achieved with metaheuristic algorithms. Metaheuristic algorithms have been used more for various problems in recent years [8,9]. Although there are many studies conducted in this context, these studies differ according to the designs and purposes of the building elements. Chakrabarty [10] studied the optimization of the design cost and material consumption with the Nonlinear program model in his study. Bekdaş and Nigdeli [11] provided the optimum design by using the TLBO algorithm in their study. Zivari et al. [12] worked on optimum weight and material optimization. Guerra and Kiousis [13] performed the optimization of the beam using a sequential quadratic programming algorithm. In the study of Chutani and Singh [14], the Particle Swarm Algorithm performed the optimum study of the reinforced concrete beam design by using Indian regulation. Nigdeli and Bekdaş [15] carried out the optimum design according to the unfavorable live load in their study. Coello et. al. [16] utilized Genetic Algorithm to achieve optimum beam design. Ulusoy et al. [17] optimized the minimum cost for the reinforced concrete beam by using Bat Algorithm (BA), Harmony Search (HS), Teaching-Learning Based Optimization (TLBO). In addition, Ulusoy et al. [18] found the optimum design of multi-span frame structures which consist of reinforced concrete by using Harmony Search.

In this study, different metaheuristic algorithms are used for comparison to the effectiveness of beam design which is utilized in various areas of structural engineering. All algorithms have different features which can be about phase number, control parameters as well as combined different features. Therefore, they affect the needed iteration number that can be enough to reach the objective function. In the second study, 3 different regulations which are ACI 318 [19], Eurocode 2 [20] and TS500 [21] are used to design the beam according to various classes of concrete.

2. Materials and Methods

2.1. The Beam Design and Regulations

Beams are one of the generally preferred building elements which are a member of frame systems in building designs and this building element may differ according to their designs. These differences affect the operation of the beam and enable it to gain different properties. It will be observed that there is a difference in the calculations when it is designed as a rectangular cross-section of the beam and a T-section beam. Firstly, in order to endure the bending moment, the cross-sections of the beam are assigned according to regulations, and it has to use the needed reinforcement area [22, 23]. Secondly, the effect of corrosion and enough capacity should be considered, when engineers design structural elements [24]. Even though the tension zone of the cantilever beams (balcony) is to be in the upper part of the beam, the two columns inside the building will be in the lower part of the beam. Such differences have a very important effect on design and reinforcement placement. The beams are reinforced in the area where the tension zone will be formed according to the dead and live load applied to it. In this way, tensile forces will be met with reinforcements with much better tensile strength than concrete under loads, and situations such as breaking or cracking in the structure will be reduced.

Each regulation has some specific formulas for design problems. Some formula differences may be due to the results of the laboratory or depending on factors such as the situation in which measures are taken as a result of the structural errors experienced in the history of the country. In this way, when the design of the structure is carried out under certain loads, besides the fact that the system has different cross-section dimensions, there may also be differences in the use of the required reinforcement area. If the reinforcement area is used more or less, its effect on the system should be considered [25]. Furthermore, if the result of the necessary reinforced area is smaller than the minimum reinforced area, it will be equal to the minimum reinforced area for 3 building codes.

Table 1 shows the beams' design constraints. The first of the constraint values given for TS500 gives the area where the depth of the stress block should be, while the second constraint is the comparison of reinforcement ratios. The reason why the 0.235* f_{cd}/f_{yd} equation is taken into account in the reinforcement ratio comparison is used to keep the deflection conditions under control [26].

For Eurocode 2, the g_1 is used to control whether compressive steel is necessary or not (k), and the g_2 restrains the stress block depth, as well as g_3 limits the maximum reinforced area.

For ACI 318, the g_1 compares to values of the stress block depth, while the g_2 compares the reinforced area. Also, all abbreviations have meanings and these are:

As	reinforcement area,
b	section width,
h	section height,
d	distance from the over-compression to the center of the longitudinal tensile reinforcement
z	internal force lever (moment lever)
fyk	characteristic yield strength of steel,
fyd	steel design yield strength,
fcd	concrete design compressive strength,
fck	characteristic compressive strength of concrete,
ρ_b	balanced reinforcement ratio

Table 1. The Beam's Constraints

Eurocode 2	$g_1 = k < 0.167$ $g_2 = z < 0.95*d$ $g_3 = \frac{A_s}{b \times h} < 0.04$
TS500	$g_1 = 0 < d - \sqrt{a} < h$ $g_2 = \text{Reinforced Area} \leq \begin{cases} 0.85 \times \rho_b \\ 0.02 \\ 0.235 \times \frac{f_{cd}}{f_{yd}} \end{cases}$
ACI 318	$g_1 = 0 < d - \sqrt{a} < h$ $g_2 = \frac{A_s}{b \times h} < 0.75*0.85*k1*(f_{ck}/f_{yk})*600/(600+f_{yk})$

Eq. (1) calculate how much money should expend on concrete, while Eq. (2) calculates the money for needed steel; furthermore, Eq. (3) contributes to finding how much money is necessary for labor and formwork as well as Eq. (4) is used for the total cost for this design.

$$C_{concrete} = C_c \times L \times \frac{(b_w \times h - A_s)}{10^6} \tag{1}$$

$$C_{concrete} = C_s \times L \times \gamma_s \times \frac{A_s}{10^6} \tag{2}$$

$$C_{formwork-labor} = (C_k + C_{ki}) \times L \times \frac{(b_w \times h)}{10^6} \tag{3}$$

$$TotalCost = C_{concrete} + C_{steel} + C_{formwork-labor} \tag{4}$$

2.2. Metaheuristic Algorithms

Metaheuristic algorithms are algorithms that are inspired by events in nature and created by forming equations as a result of observations. Although it is frequently used in fields such as engineering, economy, logistics, finance and energy systems, it can also be used in different fields. When the optimization process and structural design process are combined, it can lead to finding the optimum objective function effectively and easily [27-30]. To give examples of these algorithms; Algorithms such as Simulation Annealing (SA), Flower Pollination Algorithm (FPA), Cuckoo Algorithm (CS) [31] and Artificial Bee Colony Algorithm (ABC) [32] can be given as examples. These algorithms have been created as examples from many areas and differences of life. Some of these are the Ant Colony Algorithm developed based on the movements of the ants, the Bat Algorithm developed by utilizing the features of the Bats, the Differential Evolution with the evolutionary developments based on the population, and the Harmony Search Method inspired by ensuring that the musical piece sounds the best to the listener [33]. Although each developed algorithm has different formulas, it differs according to whether it is single-stage or multi-stage. Because of these differences, some algorithms can give more efficient results in reaching the objective functions.

2.2.1 Teaching-Learning based optimization (TLBO)

This algorithm is developed by Rao et al. [34] in 2011, inspired by the learning interaction stages between teacher-student. It consists of two phases: the teacher phase and the student phase[35]. This feature makes it superior to other algorithms. The reason is that the objective function is compared 2 times in 1 iteration, and this allows the algorithm to complete the algorithm in a shorter time by reaching the objective function in fewer iterations.

```
Begin
% All needed constraints, variables and constants should be written
% The determination of population and iteration number
% Finding moment value
% Cross-Section lengths are generated randomly in terms of variable range.
% Finding reinforcement area
        -   Finding reinforcement ratio according to reinforcement area
        -   Comparing the maximum and minimum reinforcement area
        -   Generating the initial solution matrix
        -   Controlling the constraints and penalizing the objective function
The step of Teaching-Learning Phase
% Finding the mean and best value of initial solution matrix
% Finding the teaching factor (TF)
% Generating the variables
% Finding reinforcement area
        -   Finding reinforcement ratio according to reinforcement area
        -   Comparing the maximum and minimum reinforcement area
        -   Generating the new solution matrix
        -   Controlling the constraints and penalizing the objective function
% Comparing the initial and new matrix, and choosing best one.
End
```

Fig. 1. TLBO Pseudo Code

2.2.2 Differential evolution (DE)

It is an algorithm developed by Storn and Price [36], inspired by the natural evolutionary state of species. This algorithm has been successfully applied in a lot of areas [37,38,39,40] such as engineering [41], communication [42] and many different fields. It is a random search method that simulates mutation, re-arrangement and selection steps [37]. The pseudo-code is shown in Fig. 2.

```
Begin
% All needed constraints, variables and constants should be written
% The determination of population and iteration number
% Cross-Section lengths are generated randomly
% NECESSARY EQUATIONS SHOULD BE WRITTEN in HERE
% Generating the initial solution matrix
The step of Differential Evolution
% Generating p, q as well as r which change iteration number (Mutation process)
% Crossover operation and comparing variables
% If (rand () <= CR) || (kr == randkr)
        b= b_new;
        h= h_new;
% If not (rand () <= CR) || (kr == randkr)
        b=OPT (1, kr);
        h=OPT (2, kr);
% NECESSARY EQUATIONS SHOULD BE WRITTEN in HERE
% Generating the new solution matrix
% Comparing new and initial solution matrix, and choosing the best one.
End
```

Fig. 2. Differential Evolution Pseudo Code

2.2.3 Hybrid algorithm (TLBO-Jaya)

Hybrid algorithms are generally formed by combining various algorithms within themselves. In order to develop their structures, it can be combined 2 or more algorithms [43]. These algorithms can be made by changing 1 phase of 2-phase algorithms. For example, there is Teaching and Learning phase in the TLBO algorithm, and if a Hybrid Algorithm is desired, 1 phase from other algorithms is added instead of the Learning phase (it can be Jaya) and the algorithm is completed in this way. The efficiency of the algorithm is shown in comparison with the studies and it is observed that there is a more effective optimization process in general and it reaches the objective function more efficiently. Furthermore, Hybrid Algorithms of SA, HS and BBBC which have effective features when solving problems are developed [44].

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Iteration Phase: # It include 2 phases and altering can be learning phase

Teaching Phase

$$X_{i,new} = X_{i,j} + rand()\left(X_{i,g_{best}} - |X_{i,j}|\right) - (TF)X_{i,ortalama})$$

$$\text{TF} = round\ (1 + rand\ ())$$

…..

Learning Phase → Jaya Algorithm

$$X_{i,new} = \begin{cases} AF_a < AF_b, & X_{i,j} + r()\left(X_{i,a} - X_{i,b}\right) \\ AF_a > AF_b, & X_{i,j} + r()\left(X_{i,b} - X_{i,a}\right) \end{cases}$$

(Changing between equations)

$$X'_{i,new} = X_{i,j} + rand()(X_{i,g_{best}} - |X_{i,j}|) - r()(X_{i,g_{worst}} - |X_{i,j}|)$$

Fig. 3. Hybrid Code equations' changing

Altering hybrid code can be like the Fig. 3 which includes TLBO and Jaya algorithm to combine.

2.2.4 Jaya algorithm

Jaya algorithm which has developed by Rao in 2016 [45] is a method that has a similar approach to the TLBO algorithm [33]. This algorithm is frequently used in engineering problems because its variables are collected in a narrow area and scanned, and thus efficient results are obtained. Using this algorithm is fairly straightforward to apply [46]. Jaya aims to reach the objective function in fewer iterations and it is called "Victory". Jaya equation is shown in Eq. (1).

$$X'_{i,new} = X_{i,j} + rand(\,)\left(X_{i,g_{best}} - \left|X_{i,j}\right|\right) - rand(\,)\left(X_{i,g_{worst}} - \left|X_{i,j}\right|\right) \tag{4}$$

$X'_{i,new}$ The new value of variable
$X'_{i,best}$: The i. design variable value, which is the best value for the objective function in the initial matrix
$X'_{i,worst}$ The i. design variable value, which is the worst value for the objective function in the initial matrix
$X'_{i,j}$ The value of the candidate solution i. and j. in the initial matrix
rand () Randomly assigned state between 0 and 1

2.2.5 Harmony search (HS)

Harmony Search algorithm which was inspired by musical tones and best-sounding situations was developed by Geem et al. [47]. Harmony Search has been used in miscellaneous areas [48] such as engineering problems [49], hydraulic system design [50,51], steel frames [52,53] as well as retaining walls to reach objective function. It has some equations for formulas such as PAR is known as Pitch Adjustment Rate, as well as HCMR, is known as Harmony Memory Consideration Rate which takes a number between 0 and 1. The harmony search equation is shown Eq. (2).

$$\boldsymbol{X'_{i,new}} = \begin{cases} HCMR > rand(), \;\; X_{i,min} + rand() \times \left(X_{i,max} - X_{i,min}\right) \\ HCMR < rand(), \;\; X_{i,k} + rand\left(-\frac{1}{2}, \frac{1}{2}\right) \times PAR \times \left(X_{i,max} - X_{i,min}\right) \end{cases} \tag{5}$$

$X_{i,max}$ Maximum value of the i. design variable
$X_{i,min}$ Minimum value of the i. design variable
$X_{i,k}$ The value of the candidate solution i. and j. in the initial matrix

2.2.6 Flower pollination algorithm (FPA)

It is an algorithm created by taking into account the changes in color and scent, inspired by the characteristics of flowers [54]. It enables the analysis to be completed by forming local pollination and global pollination situations within the algorithm.

3. Numerical Examples

3.1. Comparison of Different Metaheuristic Algorithms in Beam Design

Table 2 shows the design values which are restraints, variables, constants as well as the cost of the material. Fig. 4 shows beam distributed load and cross-section.

Table 2. Beam design values

Explanation	Symbol	Unit	Value
Minimum section width	b_{wmin}	mm	250
Maximum section width	b_{wmax}	mm	400
Minimum section height	h_{min}	mm	400
Maximum section height	h_{max}	mm	600
Distributed load	q	kN/m	32
Beam length	L	m	6
Compressive strength of concrete	f_{ck}	MPa	25
Yield strength of concrete	f_{yk}	MPa	420
Specific gravity of steel	γ_s	t/m³	7.86
Clear cover	d	mm	30
Cost of concrete per unit volume	C_c	TL/m³	1400
Cost of steel per unit weight	C_s	TL/ton	15050
Cost of formwork material-labour	C_k, C_{ki}	TL/m²	104-60

The objective function was generated to minimize design cost. Hence, it is important to find effective cross-sections and necessary reinforced areas for design. Moreover, these variables can change differences between their cost. For instance, when the cost of concrete increases, the ratio of concrete usage will decrease in the optimization process.

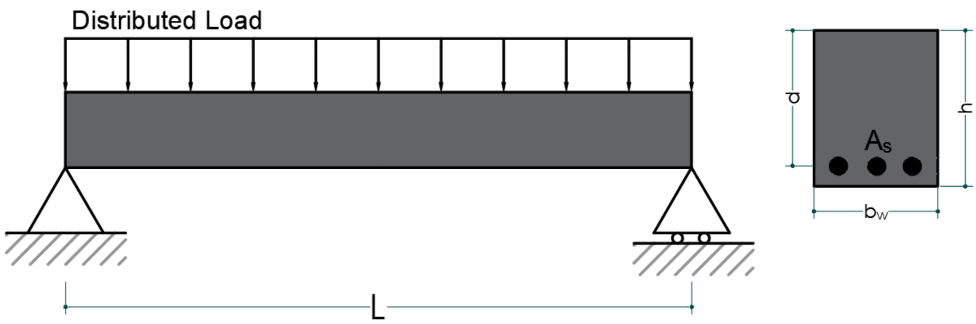

Fig. 4. Beam section and loading display

Table 3 demonstrates the result of optimizations with various algorithms which are Jaya, Teaching-Learning Based Optimization, Flower Pollination Algorithm, Hybrid Algorithm, Harmony Search as well as Differential Evolution. All of the algorithms are the approximately same cross-sections, reinforced area and cost.

Table 3. Optimization results for various algorithms

Explanation	b_w (mm)	h (mm)	Reinforced Area (mm²)	Cost (TL)
Jaya	250	410.5	1006.5	1668.8
TLBO	250	410.5	1006.5	1668.8
TLBO-Jaya	250	410.5	1006.5	1668.8
FPA	250	410.5	1006.5	1668.8
HS	250	410.5	1006.5	1668.8
DE	250	410.5	1006.5	1668.8

Table 4 illustrates the cases which are related to different running. Additionally, Case-1 has 5 runs, Case-2 has 10 runs, Case-3 has 15 runs as well as Case-4 has 20 runs. It can easily be seen that all cases show the average of runs to compare each other. Also, all cases have 2 different categories, namely Iter and S.D. Iter refers to how many average iterations the algorithm can reach the objective function. On the other hand, S.D. refers how many average (100) iterations the problem standard deviation will be 0. Also, the mean of standard deviation is taken for 100 iterations to compare the amount of changes. Standard deviation results are undeniable fact that when Hybrid and TLBO are used for problem, they generally take nearly the same value as the objective function.

Table 4. Comparisons of each algorithm

	Case-1		Case-2		Case-3		Case-4	
	Iter	S.D.	Iter	S.D.	Iter	S.D.	Iter	S.D.
JAYA	74.4	3.43	76.7	3.00	74.9	2.66	74.5	3.07
TLBO	61.4	0.016	59.6	0.02	58.8	0.016	59.9	0.02
HYBRID	35	0.0054	35.3	0.01	35.6	0.01	35.3	0.01
FPA	62.4	3.62	60	2.63	60.7	2.38	60.82	2.17
HS	10000+	4.5	10000+	3.7	10000+	3.58	10000+	4.04
DE	10000+	12.37	10000+	14.35	10000+	12.91	10000+	13.04

Although the HS approaches the objective function with less than 0.2% standard deviations (according to the average of 100 iterations) between 70-80 iterations, it is observed that it needs a lot of iterations to reach the objective function exactly. The reason for this may be that the maximum and minimum values of the variables are used in the formulas during the assignment of the cross-sections.

When the DE algorithm is used, it is similar to the HS algorithm in terms of the number of iterations to reach the objective function, and it is observed that this algorithm approaches the objective function with less than 0.75 standard deviations (according to the average of 100 iterations) in approximately 75-80 iterations. However, it is observed that there are large differences in the mean standard deviation values in 100 iterations. The most important factor affecting the formation of these differences is; It is expected to result from the analysis according to the randomly selected objective function value, instead of dealing with the best and worst values of the objective function in the iteration stage.

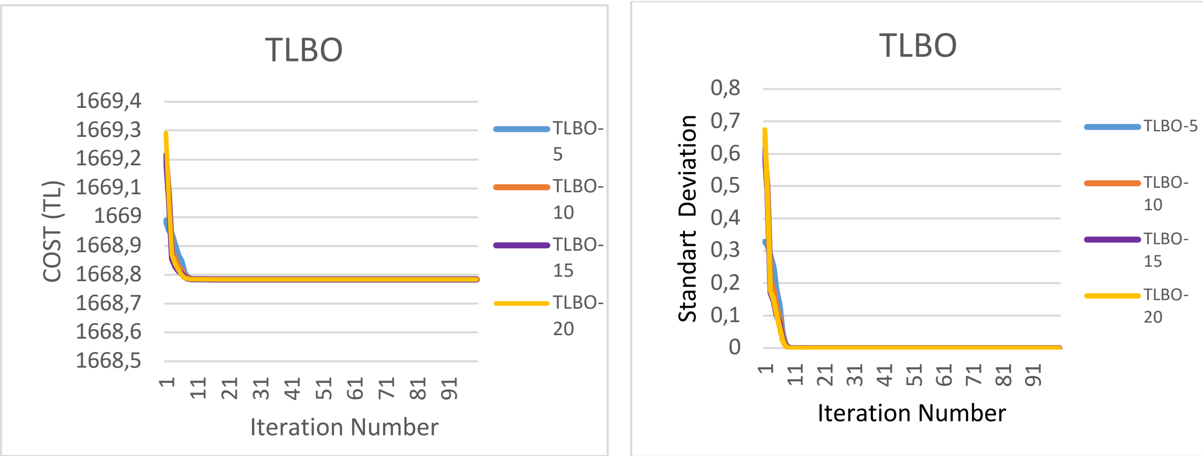

Fig. 5. TLBO results

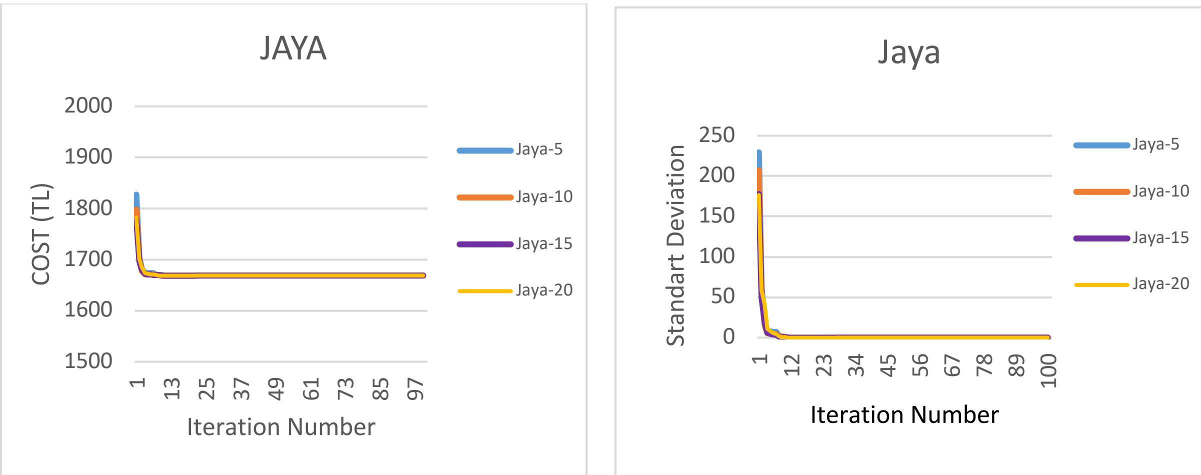

Fig. 6. Jaya Algorithms results

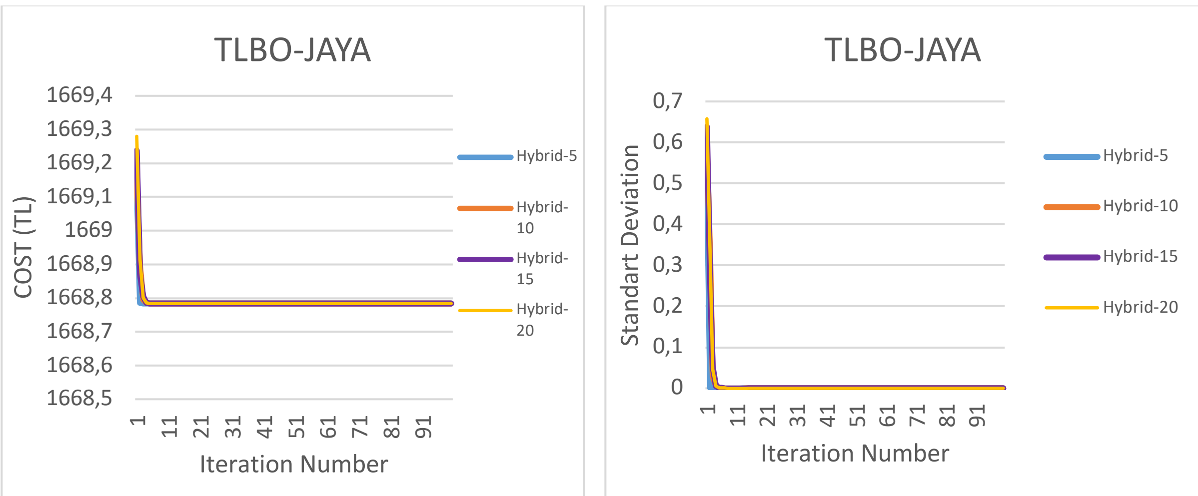

Fig. 7. Hybrid Algorithm results

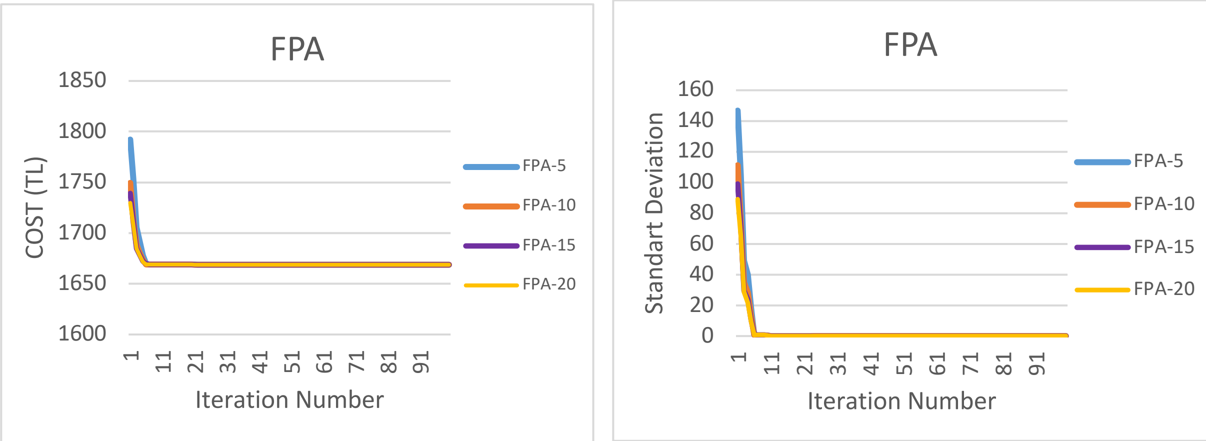

Fig. 8. Flower Pollination Algorithm results

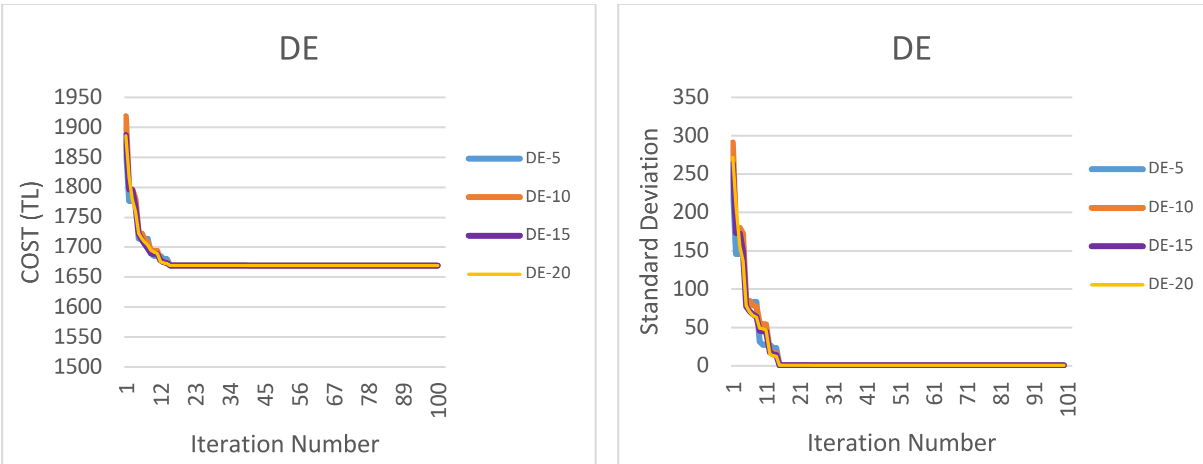

Fig. 9. Differential Evolution results

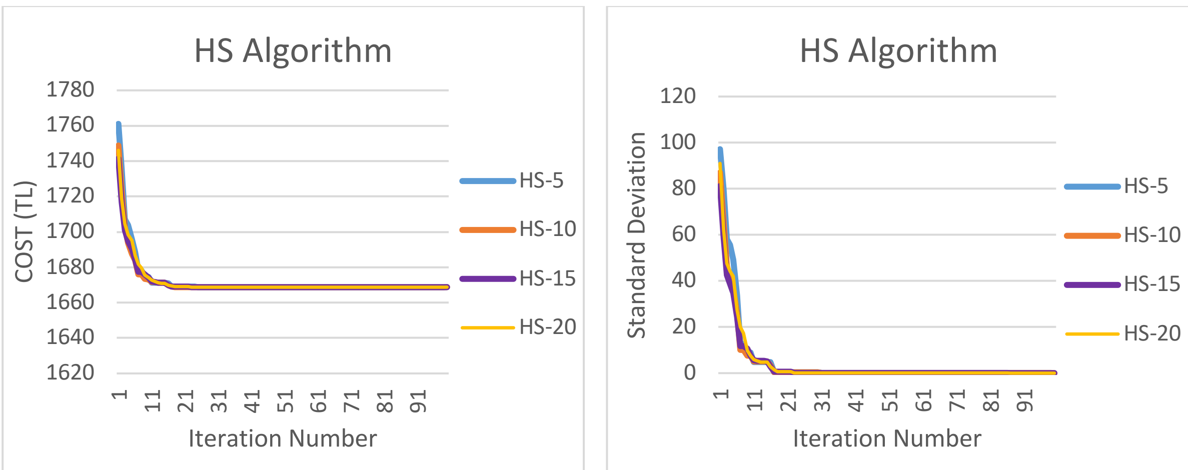

Fig. 10. Harmony Search results

Fig. (5-10) demonstrate the changing of cost and standard deviation by increasing iteration numbers. Looking at the line charts in more detail, at the beginning of the iterations, the beams' cost for Jaya algorithm is just over 1800 TL, FPA is just under 1800 TL as well as TLBO and Hybrid algorithms are approximately 1669 TL. For these graphs, differences between standard deviations also are observed and they have big differences compared to each other. At the first iteration, due to the fact that TLBO and Hybrid Algorithms have 2 phases, they approach objective functions easily compared to the other used algorithms. FPA is roughly 150 and Jaya is almost 250. DE has the biggest standard deviation. Harmony Search's standard deviations seem that it is an effective and good solution compared to DE, Jaya, and FPA. However, it cannot reach the objective function with fewer iterations. The standard deviation of TLBO and Hybrid algorithm.

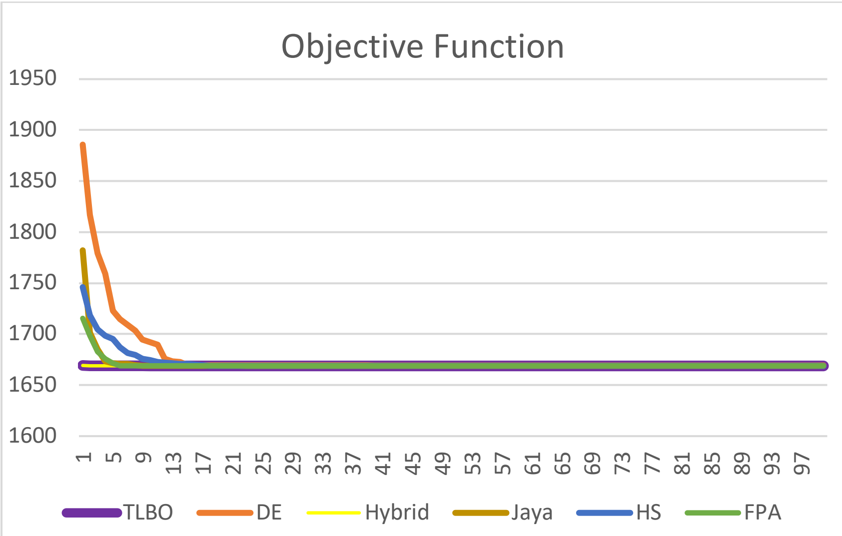

Fig. 11. Comparison of the algorithms in terms of cost

Fig. 11 compares by showing the variation of all used algorithms in this study according to the number of iterations. The X-axis shows the iteration number while Y-axis demonstrates the cost of the beam. It can easily be seen that Hybrid and TLBO algorithms are the most effective algorithms compared to the others. They generally approach the objective function in a few iterations. This feature allows complex problems to be solved easily and in a short time. Differential Evolution is the slowest one for approaching the objective function. Additionally, the initial cost is bigger than other algorithms and the second most expensive cost is from the Jaya algorithm, at approximately 1785 TL as well as the other 4 algorithms generally alter between 1668 TL and 1750 TL.

Fig. 12 illustrates the altering between all used algorithms in terms of standard deviation. Standard deviation helps us to compare differences between current matrix elements and objective function. If the standard deviation is close to 0, it can exactly say that there are not too many differences between these values and they are nearly similar. DE and Jaya make up a large proportion, at 275 and just over 175 respectively. FPA and HS have nearly 70-90 for both algorithms. TLBO and Hybrid constitute of smallest difference. Therefore, their finding costs are close to the objective function.

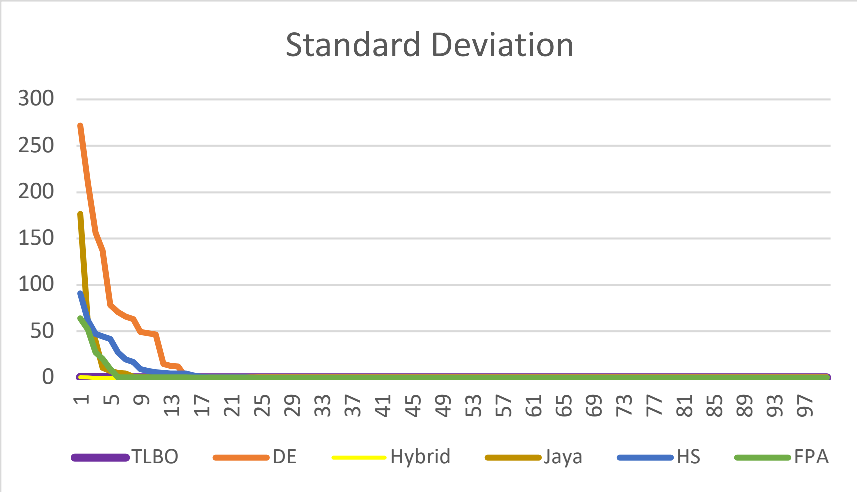

Fig. 12. Comparison algorithms in terms of standard deviations

3.2. Implementation of Beam Design according to Regulations Using Hybrid Algorithm

In the study in this section, the rectangular section reinforced concrete beam design is designed to be cost-optimal by using different regulations. ACI 318, TS500 and Eurocode 2 regulations have been added to the program for analysis of separate formulations. Hybrid Algorithm created by combining Metaheuristic Algorithms is used to achieve the objective function. The use of this type of algorithm is because it gives more efficient results than other algorithms. In section 4.1, it is observed that Hybrid Algorithm achieved much more efficient results than other algorithms, and in addition, it is observed that it reached the objective function in approximately 75% shorter iterations compared to the second-best algorithm (TLBO).

Maximum-minimum value of sections, distributed load value, the concrete class used, steel class yield strength, clear cover, steel specific gravity, and concrete-steel-formwork costs will be used as given in Table 5. In addition, cost changes that would occur if different concrete classes are used under the same specifications are also applied. These cost changes, the cost increases as the concrete compressive strength increases, the reinforcement class used will not change and there will be no difference in cost. However, with the change in the concrete class, the values to be used in the formulas will change and there will be differences in the cross-section dimensions and the reinforcement areas to be used. Due to these differences, there will be a difference in the cost value required for the beam design. Concrete classes of C25/30, C30/37 and C35/45 will be used for this study. With the change in concrete compressive strength, differences in objective functions can be observed. Table 5 shows the cost of concrete types which are increasing with the rise of the concrete strength.

Table 5. The cost of concrete

Concrete Classes	Cost of concrete (TL/m^3)
C25/30	1400
C30/37	1460
C35/45	1575

Tables 6, 7 and 8 illustrate the changing between building codes according to cross-section, reinforced area (A_s) as well as cost by using different types of concrete classes. It can easily be seen that when TS500 and Eurocode 2 are used for this problem, their results are found approximately the same. In the design process, if the using concrete class increases, the necessary amount of cost design goes up too. Moreover, b_w (width) sections are the same in both all 3 building codes and 3 various concrete classes although h (height) sections alter by changing concrete class. When the using concrete class is increased, the cost of design also will go up.

Table 6. Result of Hybrid Algorithm by using C25/30 Concrete

	b_w (mm)	h (mm)	A_s (mm²)	Cost (TL)
Eurocode	250	456.33	1060.3	1814.2
TS500	250	456.45	1060.6	1814.7
ACI 318	250	410.5	1006.5	1668.8

Table 7. Result of Hybrid Algorithm by using C30/37 Concrete

	b_w (mm)	h (mm)	A_s (mm²)	Cost (TL)
Eurocode	250	437.92	1091.6	1832
TS500	250	438.1	1091.9	1832.4
ACI 318	250	400	1019.1	1688.8

Table 8. Result of Hybrid Algorithm by using C35/45 Concrete

	b_w (mm)	h (mm)	A_s (mm²)	Cost (TL)
Eurocode	250	418.7	1136.2	1887.8
TS500	250	418.8	1136.4	1888.3
ACI 318	250	400	1003.5	1761.1

Fig. 13 shows the costs according to building regulations and the different classes of concrete. It is fact that ACI 318 is the least amount compared to others.

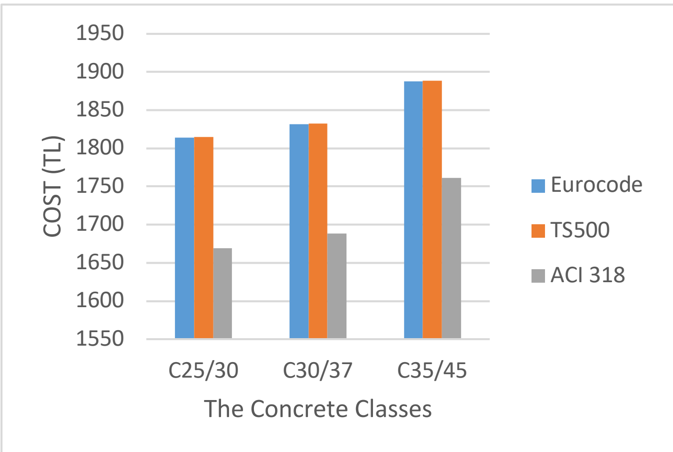

Fig. 13. The costs according to building codes

4. Discussion of Results

In this study, the rectangular reinforced concrete beam is designed ACI 318, TS500 and Eurocode 2. The first study is that ACI 318 regulation rules and boundary conditions, and algorithms are written in such a way that the system had the most optimum cross-section values

and reinforcement area in terms of cost. These algorithms are performed using a Matlab program with different metaheuristic algorithms such as TLBO, Hybrid, Jaya, FPA, HS, DE. Each algorithm differs from the other due to its features such as having different formulas and being of 1 or 2-phase algorithms. Using different algorithms in this way; When the algorithms reach the objective function, the section sizes, reinforcement areas and cost values are compared, as well as the comparison of how many iterations the algorithms reached to the optimum value and how close they got to the objective function. As a result of the optimization, it is observed that the dimensions of the beam sections, the reinforcement area to be used in the beam and the total cost value for the system are the same for each algorithm. In the case of applying a distributed load of 32 kN/m to a 6-meter-long beam, the beam width is calculated as 250 mm, the height is calculated as 410.5 mm, and the reinforcement area is calculated as 1006.5 mm^2. In the case of cost calculation, after these values are found, an expense of approximately 1668.8 TL will be expected. While TLBO and Hybrid algorithms, which have 2 phases, reach this cost value in very few iterations, it takes a little longer for other algorithms to reach the objective function. Also, FPA reaches the objective function about the same iteration number. Looking at the other algorithms, Jaya generally reaches objective function roughly in 75 iterations. In the case of using HS and DE algorithms, it has been observed that reaching the objective function is more than 10,000 iterations. However, despite being like this, it is seen that the standard deviation values of HS are very close to the objective function on average. However, it is seen that the standard deviation value of DE for 100 iterations is higher than the others, and this may be because the objective function values chosen randomly in the formulas will affect the efficient finding of the sections. Jaya, on the other hand, appears to have reached the objective function in approximately 45 iterations, even though it seems expensive at first due to the randomly assigned values.
As the second study, a rectangular reinforced concrete beam design is applied by using different regulations depending on the same loadings and material properties. In these designs, the changes between them are controlled by using different concrete classes for each regulation. As the strength of the concrete used increases, the cost value also increases. In general, section dimensions, reinforcement area and cost results are approximately the same for Eurocode 2 and TS500, while ACI 318 takes different values according to these regulations and the cost value is calculated less. When controls are made between costs, it has been observed that ACI 318 has approximately 6.5%-8.2% less cost compared to other regulations. For C25/30 concrete class, Eurocode 2, TS500 and ACI 318 design costs take different amounts, at 1814.2 TL, 1814.7 and 1668.8 respectively. C30/37 concrete class, Eurocode 2, TS500 and ACI 318 design costs take different amounts, at 1832 TL, 1832.4 and 1688.8 respectively. C35/45 concrete class, Eurocode 2, TS500 and ACI 318 design costs take different amounts, at 1887.8 TL, 1832.4 and 1761.1 respectively.

5. Conclusion

As a result of this study, these findings were obtained.

- There are various metaheuristic algorithms that are inspired by nature. They can reach the objective function in the different iterations because of differences between their formulization and the number of stages and phases.

- Hybrid algorithms that combined with 2 or more algorithms generally reach the objective function the with least iterations compared to other used metaheuristic algorithms.

- Building codes can influence the design of structures because of their design properties. Therefore, when a system is designed, differences in cross-section dimensions, reinforcement area and cost values can be observed.

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The Effects of Calibration Parameters in Muskingum Models on Flood Prediction Accuracy

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Abstract

Attenuation, time lag, outflow peak and storage are very essential factors required in flood risk prediction and flood pattern. However, the accurate prediction strongly depends on appropriate calibration of routine parameters of the model, such as weighting factor (x) and storage time constant (K). The weighting factor being used to determine storage time constant has not been given consideration in the previous studies and this could have led to inaccurate prediction in the past. In this work, a set of data obtained from an ungauged Awara river in Ondo State, Nigeria were used to test the effects of a weighting factor, x at levels ranging from 0.1-0.5 at interval of 0.1. The Muskingum model was used to obtain the storage and weighted discharge storage. It was observed that the correlation coefficient (R^2) decreases with an increase in the weighting factor (x). This implies that there is a strong relationship between storage and weighted discharge storage at 0.1-0.3 levels of x while, the relationship is fair at 0.4-0.5 levels. It is therefore appropriate to choose a value of x ranging between 0.1 and 0.3 for attenuation prediction, while values of x ranging between 0.4 and 0.5 would be appropriate for accurate prediction of both outflow peak and storage.

Keywords: Muskingum model, Awara river, hydrograph, flood risk, Attenuation, outflow peak.

1. Introduction

Flooding occurs when an area is submerged in water. It is an overspill of large amount of water to a dry land which can be caused by over spilling from rivers, streams and even excessive rainfall [1-4]. The aftermath of floods is mostly associated with destruction of properties and loss of lives [5] because it can cart away bridges, cars, houses, and even humans and also destroys crops and trees on land [6].

Flooding occurs globally and causes casualties and property loss. It is undoubtedly the most overwhelming and common natural disaster in the human world [7]. It is also reported to be the most significant proportionate number of natural disasters happening globally and over the last four decades this percentage has increased and this led to significant research towards the development of flood inundation models [8]. Flooding can occur without any prior warnings and can cause many deaths and destruction of properties if the public is not warned in advance. The

public needs to be warned in an informative and timely manner to minimize the impacts of flood. This process involves the recognition of prediction commencement, gathering and assessment of data by computerized systems, threat recognition, notification, decision generation, response activation, and public action and mitigation strategies [9].
Most flood models involve background responsiveness and research to the productivity variables for predictive application in space and time scales. The level of precision required and computational efficiency is of utmost concern [10, 11]. Calibration of Parameters in flood forecasting is very important because there is challenge of getting discharge data for model calibration for flood prediction in ungauged basin or river. Therefore, rainfall runoffs are used for model calibration in ungauged basin or river. The reliability of runoff prediction in flood forecasting depends on proper calibration of model and this calibration parameters in Muskingum models are weighting factor *(x)* and storage time constant *(K)* [12, 13].
Many researchers have made use of Muskingum model to predict flood risks, ranges from agriculture, environment, dams, bridges construction and irrigation [14-17].

Ref. [18] used Adaptive Hydraulics (AdH) model and the Finite Element Surface Water Modeling System (FESWMS) to generate a hydraulic model in the Akarcay Basin area of Turkey. They first determined the peak flood discharges consisting of three methods and observed monthly flow data (hydrographs) from gauging stations and then used Synthetic methods, SCS & Mockus, to estimate peak flood discharges and finally the rainfall-runoff relationship was considered by using the observed monthly total precipitation data. Their results showed that the AdH and FESWMS models provided good results in shallow water modeling as in the case of Akarcay Basin rivers. Also [19] analysed vulnerability of flooding among Tharu households in Nepal using data collected from household surveys, group discussions, and key informant interviews in the Thapapur Village in the Kailali district, western Tarai, Nepal. Their theory was based on pressure and release (PAR) and access models. They finalized that the Tharu people are the major residents in the study area and they preferred to live within their community and also some marginalized people selected the location for residence. They also observed that human causalities have been reduced due to easy access to cell phones which has eased effective flood warnings with suitable lead times, but agriculture production loss and other losses are still high. Lastly they concluded that subsistence agriculture-based households with small land holding sizes and less income variation are highly susceptible to flooding.
However, the effect of calibration parameters range such as x and K have not been given consideration. The chosen value of x ranges between 0 and 0.5 and some researchers choose the calibration value without necessarily considering the significant of this value on their prediction accuracy. This work therefore examined the significance of calibration parameters in Muskingum model on flood prediction accuracy and determined the effects of calibration parameters; x and K on flood risk prediction accuracy in non-linear Muskingum model. This was achieved by investigating the ways in which calibration parameters can enhance the accuracy of flood risk prediction using hydrograph procedures. In addition, the hydrograph was obtained at different calibration parameter level of weighting factor and determining the effect of variation in calibration parameter weighting factor on flood prediction.

1.1 Theoretical Background

1.1.1 Flood routing

Flood routing is a procedure applied for prediction of variations in the shape and contour of a hydrograph as water passes through a river route or a reservoir [20]. There are two types of routing which are Reservoir and Channel routing. Reservoir routing is the study of effect of flood wave entering a reservoir. While, Channel Routing is the change in the shape of a hydrograph as it travels down a channel [21]. There are two types of flood modelling namely Hydraulic and Hydrologic are routing. Hydraulic routing is the hydraulic model that involves the collecting of data related to river geometry and these data are modelled and solved numerically. On the other hand the hydrologic routing applies the continuity equation for hydrology. In simple form the inflow to the river extent is equal to the outflow of the river extent plus the change of storage. The linear and nonlinear Muskingum models which are hydrologic models are essential to estimate hydrologic parameters using recorded data in both upstream and downstream part of rivers [22, 23].

1.1.2 Muskingum models for river flood routing

The established Muskingum model with the linear storage equation was developed for a district in Ohio for the control of flood in the 1930s (Muskingum conservancy district) [23]. Hydrological method for river routing is more complex than the reservoir routing because water storage in a reach is dependent on both inflow and outflow while in the reservoir routing case, the storage is generally dependent only on the outflow from the reservoir. The Muskingum Equation is:

$$\frac{ds}{dt} = I - Q \tag{1}$$

$$S = K[xI + (1 - x)Q] \tag{2}$$

Where S = Total Storage, K = Storage-time constant, x = Weighting factor takes value between 0 to 0.5, I = Inflow discharge, Q = Outflow discharge.
In this study, the common Muskingum equation as introduced below is used for flood routing computations:

$$O_2 = C_0I_2 + C_1I_1 + C_2O_1 \tag{3}$$

In which,

$$C_0 = \frac{(-kx+0.5\Delta t)}{k-kx+0.5\Delta t} \tag{4}$$

$$C_1 = \frac{(kx+0.5\Delta t)}{k-kx+0.5\Delta t} \tag{5}$$

$$C_2 = \frac{k-kx-0.5\Delta t}{k-kx+0.5\Delta t} \tag{6}$$

C_0, C_1 and C_2 are coefficients of routing defined in terms of t, K and x as above.

I_1 = Inflow discharge at time t, I_2 = Inflow discharge at time $t+\Delta t$, O_1 = Outflow discharge at time t, O_2 = Outflow discharge at time $t+\Delta t$, Δt = time interval, K and x are the storage-time constant and weighting factor parameters which should be estimated through the calibration process [24]. K and x are the parameters to be determined from observations which have a value reasonably close to the flow travel time through the river reach, and x usually ranging between 0 and 0.5. Therefore, the key objective of the Muskingum model is to estimate the parameters K and x [25]. It is noted that the friction slope varies inversely with the area of the flow so that the value of the parameter x will be less than 0.5. The result has a value of x greater than 0.5, which would indicate amplification at all frequencies.

2. Materials and Methods

The data used for this work was gotten from [14, 15, 26] which was from a report of a dam located in Ondo North senatorial district. The procedure for routine started with the hydrologic parameters weighting factor *(x)* of 0.1 and time interval *(Δt)* of 30 days. The storage was calculated using the inflow and outflow data with the time interval where the initial outflows is equal to the initial inflows when the flood has not arrived. Then estimate the next storage for individual weighting factor *(x)* using the formula: $S = K[xI + (1 - x)Q]$.

Thereafter, a plot of a chosen weighting factor (x) against the calculated was obtained to get storage-time constant *(k)*. Then the values of C_0, C_1 and C_2 were calculated from Eqs. (4-6). Later the new outflow was calculated using equation (3) and the plot of the graph of the inflow peak with the new calculated outflow *(Q)*. The above steps were repeated for other set of values of weighting factor *(x)* at interval of 0.1. The process for the work flow for this work is shown in Figure 1.

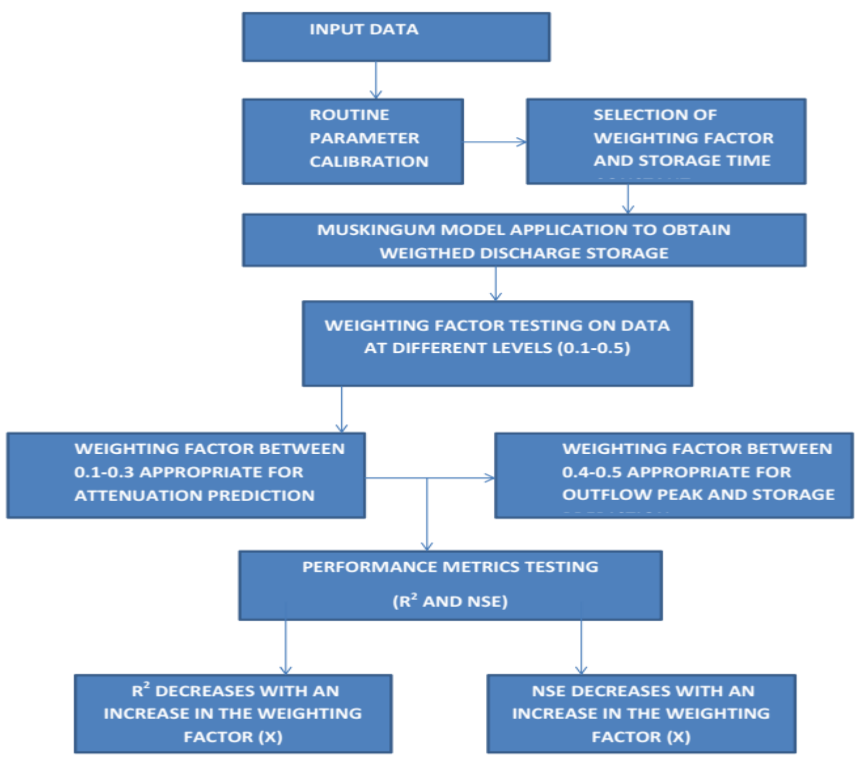

Fig. 1. Flow chart for the methodology for this work

3. Results and Discussion

The raw data extracted from detailed project reports from [26] is presented in Table 1 and the results of inflow and calculate storage with weighting factor (x) at 0.1, 0.2, 0.3, 0.4, and 0.5 respectively using equation 13 with Maple 2020 is presented in table 2 and was obtained in stepwise order; Columns 1-3 were gotten from the raw data obtained from detailed project report from [26]. Column 4: subtract column 3 from column 2 to obtain (I – O). Column 5: average of column 3 (adding two cells in column 3 divide it by 2) to obtain Avg (I – O). Column 6 is the multiplication of column 5 by 30days (change in time) to obtain ΔS=Col. 5xΔt and column 7 is the addition of first cell in column 7 that is 0 to the first cell in column 6 to obtain $S=\sum \Delta S$. Column 8-12 is computed using the equation 13 with x at 0.1, 0.2, 0.3, 0.4 and 0.5.
Tables 3,4,5,6 and 7 shows the calculated outflow at x = 0.1, 0.2, 0.3, 0.4, and 0.5. Column 1 is the time in days when the inflow was recorded with the interval of 30days for 12 months. Column 2 is the inflow rate in m^3/s per time interval. Column 3 is the product of routing coefficient C_0 and Inflow rate I_2. Column 3 is the product of routing coefficient C_1 and initial inflow rate I_1. Column 4 is the product of routing coefficient C_2 and initial outflow rate O_1. Column 5 is the addition of columns 3, 4, and 5 to give the calculated outflow Q in m^3/s.

Table 1. Raw data from Awara Dam/Oyimo River

Time (days)	Inflow (m^3/s)	Outflow (m^3/s)
0	0.01	0.01
30	0.002	0.009
60	0.064	0.014
90	0.979	0.156
120	0.105	0.4
150	0.129	0.275
180	0.149	0.214
210	0.131	0.183
240	0.161	0.164
270	0.128	0.159
300	0.035	0.134
330	0.067	0.096
360	0	0.074

Table 2. Comprehensive table showing the calculated storage.

Time (days)	**Inflow (m3/s)**	**Outflow (m3/s)**	**(I -O)**	**Avg(I -O)**	**ΔS=Col. 5xΔt**	**S=∑ΔS**	$[xI + (1-x)Q]\ (m^3/s)$				
					m3/s.day	m3/s.day	*x=0.1*	*x=0.2*	*x=0.3*	*x=0.4*	*x=0.5*
0	0.01	0.01	0			0.000	0.01	0.01	0.01	0.01	0.01
30	0.002	0.009	-0.007	-0.0035	-0.105	-0.105	0.0083	0.0076	0.0069	0.0062	0.0055
60	0.064	0.014	0.05	0.0215	0.645	0.540	0.019	0.024	0.029	0.034	0.039
90	0.979	0.156	0.823	0.4365	13.095	13.635	0.2383	0.3206	0.4029	0.4852	0.5675
120	0.105	0.4	-0.295	0.264	7.92	21.555	0.3705	0.341	0.3115	0.282	0.2525
150	0.129	0.275	-0.146	-0.2205	-6.615	14.940	0.2604	0.2458	0.2312	0.2166	0.202
180	0.149	0.214	-0.065	-0.1055	-3.165	11.775	0.2075	0.201	0.1945	0.188	0.1815
210	0.131	0.183	-0.052	-0.0585	-1.755	10.020	0.1778	0.1726	0.1674	0.1622	0.157
240	0.161	0.164	-0.003	-0.0275	-0.825	9.195	0.1637	0.1634	0.1631	0.1628	0.1625
270	0.128	0.159	-0.031	-0.017	-0.51	8.685	0.1559	0.1528	0.1497	0.1466	0.1435
300	0.035	0.134	-0.099	-0.065	-1.95	6.735	0.1241	0.1142	0.1043	0.0944	0.0845
330	0.067	0.096	-0.029	-0.064	-1.92	4.815	0.0931	0.0902	0.0873	0.0844	0.0815
360	0	0.074	-0.074	-0.0515	-1.545	3.270	0.0666	0.0592	0.0518	0.0444	0.037

Table 3. Inflow and Calculated outflow data with $x = 0.1$

Time (days)	Inflow (m^3/s)	C_oI_2	C_1I_1	C_2O_1	Q (m^3/s)
0	0.01	0			0.010
30	0.002	0.0003	0.0030	0.0056	0.009
60	0.064	0.0084	0.0006	0.0051	0.014
90	0.979	0.1281	0.0195	0.0079	0.155
120	0.105	0.0137	0.2983	0.0878	0.400
150	0.129	0.0169	0.0320	0.2257	0.275
180	0.149	0.0195	0.0393	0.1550	0.214
210	0.131	0.0171	0.0454	0.1207	0.183
240	0.161	0.0211	0.0399	0.1034	0.164
270	0.128	0.0167	0.0491	0.0928	0.159
300	0.035	0.0046	0.0390	0.0895	0.133
330	0.067	0.0088	0.0107	0.0751	0.095
360	0	0.0000	0.0204	0.0534	0.074

Table 4. Inflow and Calculated outflow data with $x = 0.2$

Time (days)	Inflow (m^3/s)	C_oI_2	C_1I_1	C_2O_1	Q (m^3/s)
0	0.01	0			0.01
30	0.002	0.0001	0.0044	0.0050	0.0095
60	0.064	0.0038	0.0009	0.0048	0.0095
90	0.979	0.0584	0.0279	0.0048	0.0911
120	0.105	0.0063	0.4266	0.0460	0.4789
150	0.129	0.0077	0.0458	0.2416	0.2951
180	0.149	0.0089	0.0562	0.1489	0.2140
210	0.131	0.0078	0.0649	0.1079	0.1807
240	0.161	0.0096	0.0571	0.0912	0.1579
270	0.128	0.0076	0.0702	0.0796	0.1574
300	0.035	0.0021	0.0558	0.0794	0.1373
330	0.067	0.0040	0.0153	0.0693	0.0885
360	0	0.0000	0.0292	0.0447	0.0739

Table 5. Inflow and Calculated outflow data with $x = 0.3$

Time (days)	Inflow (m^3/s)	C_oI_2	C_1I_1	C_2O_1	$Q(m^3/s)$
0	0.01	0.0000			0.0100
30	0.002	0.0000	0.0060	0.0039	0.0100
60	0.064	0.0004	0.0012	0.0039	0.0055
90	0.979	0.0058	0.0385	0.0021	0.0465
120	0.105	0.0006	0.5897	0.0182	0.6085
150	0.129	0.0008	0.0632	0.2384	0.3024
180	0.149	0.0009	0.0777	0.1185	0.1971
210	0.131	0.0008	0.0897	0.0772	0.1677
240	0.161	0.0009	0.0789	0.0657	0.1456
270	0.128	0.0008	0.0970	0.0570	0.1548
300	0.035	0.0002	0.0771	0.0606	0.1379
330	0.067	0.0004	0.0211	0.0540	0.0755
360	0	0.0000	0.0404	0.0296	0.0699

Table 6. Inflow and Calculated outflow data with $x = 0.4$

Time (days)	Inflow (m^3/s)	C_oI_2	C_1I_1	C_2O_1	Q (m^3/s)
0	0.01	0.0000			0.01
30	0.002	0.0000	0.0080	0.0023	0.0102
60	0.064	-0.0014	0.0016	0.0023	0.0025
90	0.979	-0.0216	0.0509	0.0006	0.0298
120	0.105	-0.0023	0.7789	0.0068	0.7833
150	0.129	-0.0029	0.0835	0.1775	0.2582
180	0.149	-0.0033	0.1026	0.0585	0.1578
210	0.131	-0.0029	0.1185	0.0358	0.1514
240	0.161	-0.0036	0.1042	0.0343	0.1350
270	0.128	-0.0028	0.1281	0.0306	0.1558
300	0.035	-0.0008	0.1018	0.0353	0.1364
330	0.067	-0.0015	0.0278	0.0309	0.0573
360	0	0.0000	0.0533	0.0130	0.0663

Table 7. Inflow and Calculated outflow data with *x = 0.5*

Time (days)	**Inflow (m^3/s)**	**C_0I_2**	**C_1I_1**	**C_2O_1**	**Q (m^3/s)**
0	0.01	0			0.01
30	0.002	0.0000	0.0100	0.0002	0.0102
60	0.064	-0.0012	0.0020	0.0002	0.0010
90	0.979	-0.0186	0.0640	0.0000	0.0454
120	0.105	-0.0020	0.9790	0.0009	0.9779
150	0.129	-0.0025	0.1050	0.0186	0.1211
180	0.149	-0.0028	0.1290	0.0023	0.1285
210	0.131	-0.0025	0.1490	0.0024	0.1490
240	0.161	-0.0031	0.1310	0.0028	0.1308
270	0.128	-0.0024	0.1610	0.0025	0.1611
300	0.035	-0.0007	0.1280	0.0031	0.1304
330	0.067	-0.0013	0.0350	0.0025	0.0362
360	0	0.0000	0.0670	0.0007	0.0677

3.1. Computation of coefficients of routing

C_0, C_1 and C_2 are coefficients of routing defined in terms of *t, K and x* as above i.e:

$$C_0 = \frac{(-kx + 0.5\Delta t)}{k - kx + 0.5\Delta t}$$

$$C_1 = \frac{(kx + 0.5\Delta t)}{k - kx + 0.5\Delta t}$$

$$C_2 = \frac{k - kx - 0.5\Delta t}{k - kx + 0.5\Delta t}$$

For *x = 0.1 and k = 59.873,* $\Delta t = 30$days, then;

$$C_0 = \frac{(-59.873\times 0.1 + 0.5\times 30)}{59.873 - 59.873\times 0.1 + 0.5\times 30}; C_0 = 0.1308$$

$$C_1 = \frac{(59.873\times 0.1 + 0.5\times 30)}{59.873 - 59.873\times 0.1 + 0.5\times 30}; C_1 = 0.3047$$

$$C_2 = \frac{59.873 - 59.873\times 0.1 - 0.5\times 30}{59.873 - 59.873\times 0.1 + 0.5\times 30}; C_2 = 0.5645$$

For x = 0.2 and k = 56.933, $\Delta t = 30 days$

$$C_0 = \frac{(-56.933\times 0.2 + 0.5\times 30)}{56.933 - 56.933\times 0.2 + 0.5\times 30}; C_0 = 0.0597$$

$$C_1 = \frac{(56.933\times 0.2+0.5\times 30)}{56.933-56.933\times 0.2+0.5\times 30};\ C_1 = 0.4358$$

$$C_2 = \frac{56.933-56.933\times 0.2-0.5\times 30}{56.933-56.933\times 0.2+0.5\times 30};\ C_2 = 0.5045$$

For x = 0.3 and k = 49.037, $\Delta t = 30 days$

$$C_0 = \frac{(-49.037\ \times 0.3+0.5\times 30)}{49.037\ -49.037\ \times 0.3+0.5\times 30};\ C_0 = 0.0059$$

$$C_1 = \frac{(49.037\times 0.3+0.5\times 30)}{49.037-49.037\ \times 0.3+0.5\times 30};\ C_1 = 0.6023$$

$$C_2 = \frac{49.037-49.037\times 0.3-0.5\times 30}{49.037\ -49.037\ \times 0.3+0.5\times 30};\ C_2 = 0.3918$$

For x = 0.4 and k = 39.646 $\Delta t = 30 days$

$$C_0 = \frac{(-39.646\times 0.4+0.5\times 30)}{39.646-39.646\times 0.4+0.5\times 30};\ C_0 = 0.0221$$

$$C_1 = \frac{(39.646\times 0.4+0.5\times 30)}{39.646-39.646\times 0.4+0.5\times 30};\ C_1 = 0.7956$$

$$C_2 = \frac{39.646-39.646\times 0.4-0.5\times 30}{39.646\ -39.646\ \times 0.4+0.5\times 30};\ C_2 = 0.2266$$

For x = 0.5 and k = 31.161 $\Delta t = 30 days$

$$C_0 = \frac{(-31.161\times 0.5+0.5\times 30)}{31.16-31.161\times 0.5+0.5\times 30};\ C_0 = -0.0190$$

$$C_1 = \frac{(31.161\times 0.5+0.5\times 30)}{31.161-31.16\times 0.5+0.5\times 30};\ C_1 = 1$$

$$C_2 = \frac{31.161-31.161\times 0.5-0.5\times 30}{31.161\ -31.161\ \times 0.5+0.5\times 30};\ C_2 = 0.0190$$

Figure (2) shows the plots of storage against weighted discharge storage for each level of weighting factor (x) used in this work. The storage time constant (k) was obtained from the equation of the plot for each level. It was observed that x varies inversely proportional to storage constant K because K decreases with an increase in x. Figure 2(a) has the equation of $59.873x + 0.647$ with a correlation coefficient, R^2 = 0.9999. Thus, parameter K is 59.873. Figure 2b has equation of $56.933x + 0.2499$ with a correlation coefficient, R^2 = 0.9451. Thus, parameter K is56.933. Figure 2(c) has equation of $49.037x + 0.8784$ with a correlation coefficient, R^2 = 0.8091. Thus, parameter K is 49.037. Figure 2(d) has equation of $39.646x + 2.2358$ with a correlation coefficient, R^2 = 0.6502. Thus, parameter K is 39.646. Figure 2(e) has equation of $31.161x + 3.4697$ with a correlation coefficient, R^2 = 0.5079. Thus, parameter K is 31.161. It was observed that correlation coefficient (R^2) decreases with an increase in the weighting factor (x). The correlation coefficients (R^2) are 0.9999, 0.9451, 0.8091, 0.6502, and 0.5079 at 0.1, 0.2, 0.3, 0.4 and 0.5 levels respectively. This implies that there is a strong relationship between storage and weighted discharge storage at 0.1, 0.2 and 0.3 levels of x (Figures 2a-c), while, the relationship is fair at 0.4 and 0.5 levels (Figures 2d-e).

Table 8. The Summary of the Results

S/N	*x*	K	R^2	NSE	Inflow peak (m^3/s)	Outflow Peak (m^3/s)	Attenuation (m^3/s)	Time Lag (days)
1.	0.1	59.873	0.9999	0.95	0.979	0.3998	0.5792	30
2.	0.2	56.933	0.9451	0.78	0.979	0.4789	0.5001	30
3.	0.3	49.037	0.8091	0.51	0.979	0.6085	0.3705	30
4.	0.4	39.646	0.6502	0.14	0.979	0.7833	0.1957	30
5.	0.5	31.161	0.5079	-0.35	0.979	0.9779	0.0011	30

NB: Nash–Sutcliffe model efficiency coefficient (NSE)

It can be clearly seen from the equations of the plots of storage against weighted discharge storage that the intercepts are negative at levels 0.1 and 0.2 of x while they are positive for levels 0.3, 0.4 and 0.5. The maximum stage of water occurs when the outflow and inflow rates are equal. As inflow reduces, the reservoir will begin to drain and the stage will reduce. When outflow rate is less than the inflow rate, water temporarily stores in the reservoir, this is called storage. The storage was found to be -0.647, -0.2499, 0.8784, 2.2358 and 3.4697 at levels 0.1, 0.2, 0.3, 0.4 and 0.5 of x respectively. This implies that there is variation in the storage at different levels of x. Thus, the storage increases with an increase in level of weighting factor x for the Muskingum routine model.

Figure 3 shows the hydrograph obtained at each level of x. From the hydrograph, attenuation and time lag were obtained. Weighting factor varies inversely proportional to storage time constant (K). It was observed that attenuation is inversely proportional to the weighting factor (x) and directly proportional to storage time constant (K). This implies that the higher the value of weighting factor (x) chosen for calibration the lower the attenuation obtained. Outflow peak is directly proportional to the weighting factor (x) and inversely proportional to storage time constant (K). Inflow peak is constant for every level of weighting factor (x) and storage time constant (K). Time lag is constant at all levels of x and K. This implies that the chosen weighting factor (x) in the calibration does not have influence on the time lag in the prediction, but it has significance effect on attenuation. The results are summarized in Table 8.

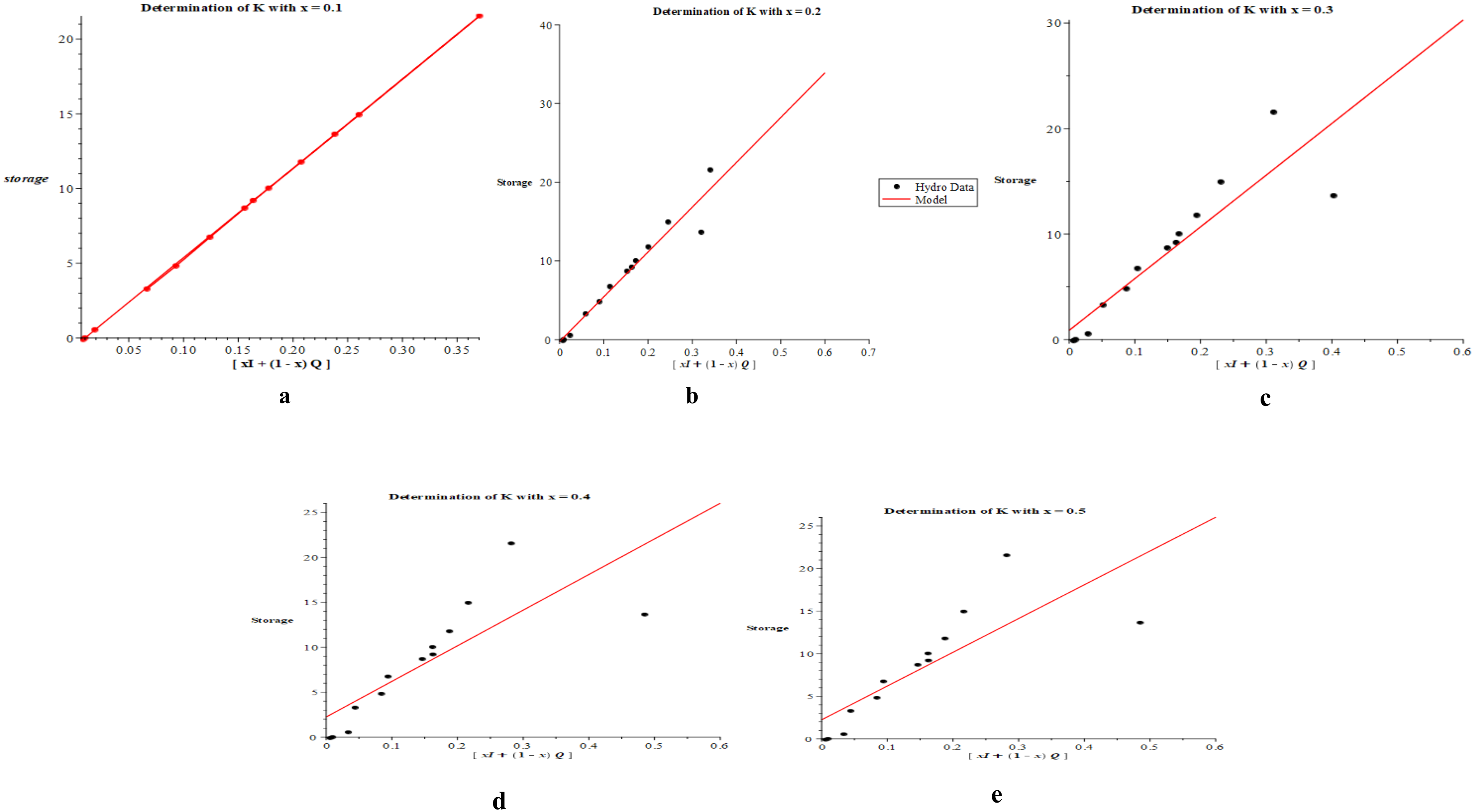

Fig. 2. Plot of Storage (m^3/s.days) against $[xI+(1-x)Q]$ (m^3/s) when *(a)* $x = 0.1$ *(b)* $x = 0.2$ *(c)* $x = 0.3$ *(d)* $x = 0.4$ *(e)* $x = 0.5$

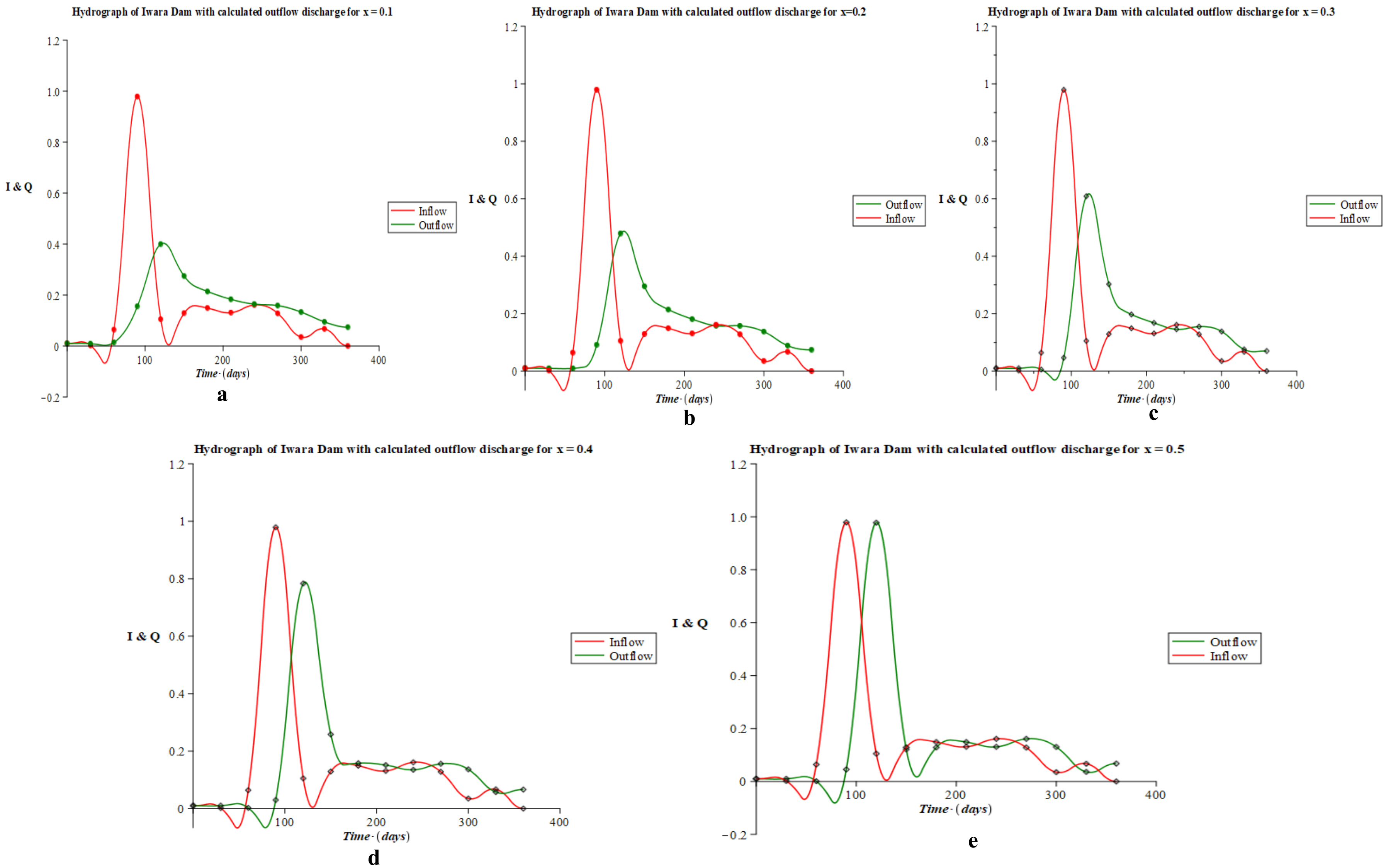

Fig. 3. Plot of Inflow (I) & Outflow (Q) $m^3/s \times 10^6$ against Time (days) when *(a) x=0.1 (b) x=0.2 (c) x=0.3 (d) x=0.4 (e) x=0.5*

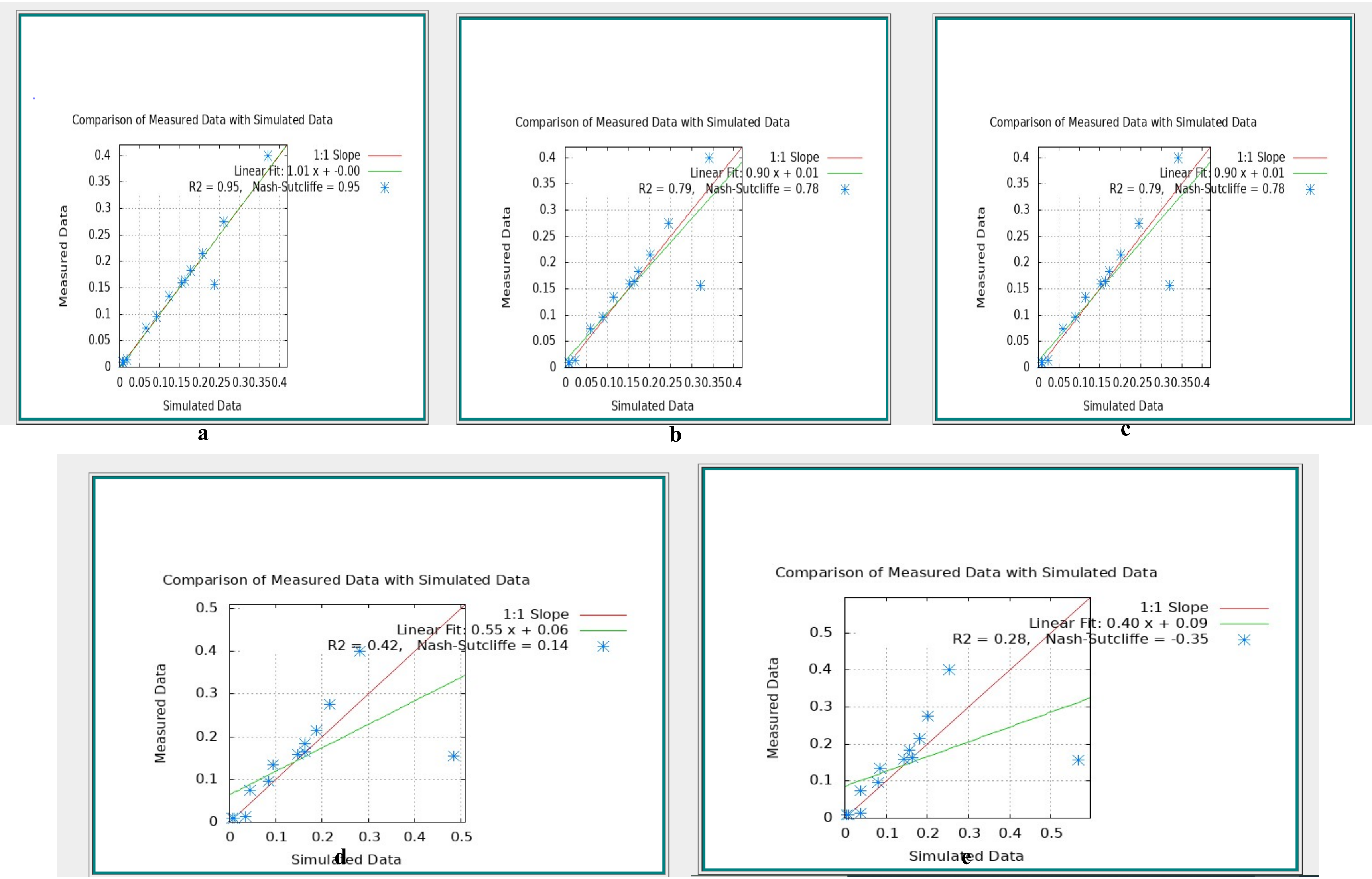

Fig. 4. Plot showing comparison of simulated and measured data for NSE when *(a) x=0.1 (b) x=0.2 (c) x=0.3 (d) x=0.4 (e) x=0.5*

An efficiency less than zero (NSE < 0) occurs when the observed mean is a better predictor than the model data so values of the NSE nearer to 1, suggest a model with more predictive skill. The observed mean for the experimental data is 0.145231. So the values of x=0.1 to 0.3 are more acceptable for the prediction based on the NSE. A test significance for NSE to assess its robustness has been proposed whereby the model can be objectively accepted or rejected based on the probability value of obtaining NSE greater than some subjective threshold (Figure 4).

Nash–Sutcliffe efficiency can be used to quantitatively describe the accuracy of model outputs other than discharge. This indicator can be used to describe the predictive accuracy of other models as long as there is observed data to compare the model results to. For example, Nash–Sutcliffe efficiency has been reported in scientific literature for model simulations of discharge; water quality constituents such as sediment, nitrogen, and phosphorus loading [27]. Other applications are the use of Nash–Sutcliffe coefficients to optimize parameter values of geophysical models, such as models to simulate the coupling between isotope behavior and soil evolution [28].

4. Conclusion

There are essential factors like attenuation, time lag, outflow peak and storage which are required in flood risk prediction and flood pattern. Nevertheless, an accurate prediction strongly depends on appropriate calibration of routine parameters of the flood model, such as weighting factor (x) and storage time constant (K) but the weighting factor being used to determine storage time constant has not been given consideration in past literatures and this could have led to inaccurate prediction in the past.

The Muskingum model was used to obtain the routing parameters and it was observed that all the perform metrics applied decreased with an increased weighting factor (x) which suggests that there is a strong correlation between storage and weighted discharge storage at 0.1-0.3 levels of x while the relationship is fair at 0.4-0.5 levels.

It is therefore appropriate to choose a weighing factor between 0.1 and 0.3 for attenuation prediction, while a weighting factor between 0.4 and 0.5 would be appropriate for accurate prediction of both outflow peak and storage. The weighting factor (x) varies inversely proportional to storage time constant (K), which corroborate with the previous studies. However, the two calibration parameters vary with attenuation and outflow peak. The calibration parameters have a significant effect on both outflow peak and attenuation, which give vital information on the level of risk from flood modeling. Thus, in order to have a good attenuation prediction, a lower value of x will be appropriate. This is so, because x is inversely proportional to the value of K, while x is directly proportional with the outflow peak. This implies that the value of x cannot be chosen arbitrarily because it could lead to inaccurate predictions and this could also lead to over or under prediction in outflow peak.

However, it was observed that the calibration parameter variation does not affect both the inflow peak and time lag of prediction modeling. Based on the research conducted, it is recommended that; in order to have a good attenuation prediction, a level of x ranging from 0.1-0.3 would be appropriate. This is so because as the value of x decreases, the value of attenuation increases. A level of x ranging from 0.4-0.5 would be appropriate for good outflow peak and storage prediction because as the value of x increases, the value of outflow peak and storage increases.

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Conflict of Interest

The authors declare no competing interest

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Optimum Design of Elastic Continuous Foundations with The Artificial Bee Colony Method

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Abstract

The study presents the investigation of the elastic behavior of the soil in the optimal design of continuous foundations according to the rigid solid case. For the investigation, the optimization algorithm that can find optimal section and reinforcement details of continuous foundations has been developed. The developed algorithm uses one of the well-known meta-heuristic methods named the artificial Bee Colony method to find the optimal design. The Winkler spring hypothesis (analytic solution) is used to calculate internal forces and stresses in elastic continuous foundations. We used the real-size design example previously used in the literature to test the elastic soil effect and algorithm performance. The obtained results show that the current algorithm performs well, and lower cost values are obtained in the elastic design.

Keywords: Continuous foundation design, Elastic line method, Optimization, Artificial Bee Colony

1. Introduction

The continuous foundation is the type of shallow foundation obtained by combining the single foundations in that direction if the size of the foundation in one direction is large in the foundation design. To carry the loads coming from the building and transfer them to the ground in a healthy way, continuous foundations must be designed following the design guidelines. In addition to the suitability of design codes, designing the foundation at an affordable cost is an important parameter. For this reason, an ideal continuous foundation should be both feasible for the design conditions and at minimum cost. However, optimizing such structures is a very complex and difficult task since these structures depend on many parameters such as foundation length, foundation width, foundation thickness, reinforcement length, reinforcement diameter, concrete class, and complex limitation functions.
The optimal design of reinforced concrete (RC) structures is one of the common types of structural optimization problems. In the past, researchers tried to search optimal design parameters for RC retaining walls using different algorithms. Mostly they considered the objective function as the minimum cost.[1-7] Apart from the cost function, researchers used CO2 emission, minimum sizing, and weight objective functions [8-15]. In the optimal design of RC retaining walls following cases were investigated: the performance of various metaheuristic methods [16-18], investigating the effect on the minimum cost for different situations [14, 19, 20].

Apart from retaining walls, studies on the optimum design of different RC structural members are available in the literature such as columns, beams [21-25], frames [26-38], slabs [39-43], pile foundations [44-46], shear walls [47], prestressed RC bridge, RC console bearing wall [27, 37, 48-50].

Meta-heuristic techniques, mostly inspired by nature, have been successfully applied in the optimization of steel and RC structures [12, 51-55]. The Artificial Bee Colony (ABC) method developed by Karaboğa [56] is a well-known metaheuristic algorithm. ABC performed well in structural optimization problems such as steel frames [57], RC columns [58], and retaining walls [59]. Therefore, ABC is a candidate method that performs highly in the presented optimization problem [58, 60-64] and is chosen as the optimization method for the study.

There are studies in the literature on the optimum design of foundations, especially on the optimum design of shallow foundation types. In these studies, the objective functions usually are the minimization of the cost and the CO2 emission [65-74]. Although there are studies for the optimum design of continuous foundations in the literature, the soil is modeled as rigid in these studies [69, 74]. In addition, no study has been found on the effect of elastic soil's behavior on the optimum design. The main motivation for the study is to develop an algorithm that calculates the optimum design of continuous foundations in elastic soil and to present novel results to the literature on the effect of elastic soil behavior on optimum cost. For this purpose, we developed an optimization program in Visual Basic programming language and tested the developed program on the literature example. We optimized the example considering both rigid and elastic behaviors.

The remainder of the manuscript is summarized as follows. Chapter 2 contains information about the mathematical modeling of continuous foundations, theoretical information about the analysis of elastic continuous foundations, the definition of the optimization problem, and the background of the ABC method. Chapter 3 gives details of the example problem and the results. In the last chapter, the discussion and conclusion of the results are available.

2. Methodology

2.1.Analysis of elastic foundations

For continuous foundations to give a realistic result, the soil can be assumed to be elastic. In the study, the Winkler spring hypothesis is used to model elastic soil behavior [75]. In this hypothesis, the continuous foundation is modeled as a beam resting on elastic springs, and the internal effects (shear force and moment) are calculated under the loads from the superstructure (See Figure 1).

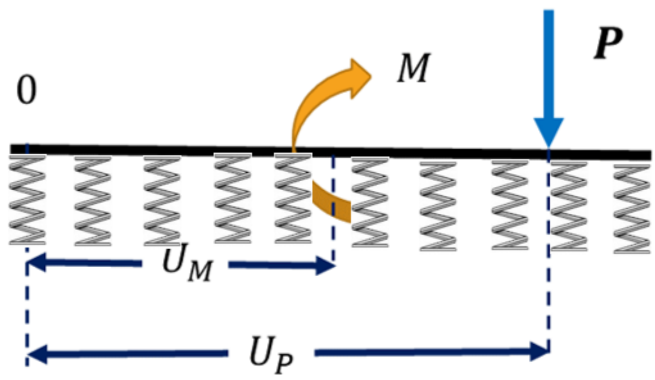


Fig. 1 An example of an elastic foundation

The cross-sectional effects for the continuous foundation positioned on the elastic foundation are analytically calculated using a solution of the differential equation as follows:

$$EI\frac{d^4y(x)}{dx^4} = q - ky(x) \tag{1}$$

where, *E* is the young modulus of concrete used in the foundation, *I* is the moment of inertia of the foundation cross-section, *y(x)* is the deflection function of the foundation, and *q* represents the loads from the superstructure. After solving the differential equation analytically, the soil stress ($\sigma(x)$), moment ($M(x)$), and shear force ($V(x)$) equations are obtained as follows:

$$\begin{aligned}\sigma(x) = k_0 \Big[y_0\, F_1(\lambda x) + \frac{1}{\lambda}V_0F_2(\lambda x) - \frac{1}{\lambda^2 EI}MF_3(\lambda x) - \frac{1}{\lambda^3 EI}V_0F_3(\lambda x)\\ - \frac{1}{\lambda^2 EI}MF_3(\lambda(x - U_M) + \frac{k}{\lambda^2 EI}PF_4\big(\lambda(x - U_p)\big)\Big]\end{aligned} \tag{2}$$

$$\begin{aligned}M(x) = M_0F_1(\lambda x) + \frac{1}{\lambda}V_0F_2(\lambda x) + \frac{k}{\lambda^2}y_0\,\mathrm{F}_3(\lambda x) + \frac{k}{\lambda^3}\theta_0\mathrm{F}_4(\lambda x)\\ + M\mathrm{F}_1(\lambda(x - U_M) - \frac{1}{\lambda}PF_2\big(\lambda(x - U_p)\big)\end{aligned} \tag{3}$$

$$\begin{aligned}V(x) = V_0F_1(\lambda x) + \frac{k}{\lambda}y_0F_2(\lambda x) + \frac{k}{\lambda^2}V_0\,\mathrm{F}_3(\lambda x) - 4\lambda M_0F_4(\lambda x)\\ - 4\lambda\mathrm{M}F_4(\lambda(x - U_M) - PF_1\big(\lambda(x - U_p)\big)\\ \lambda = \sqrt[4]{K/4EI}\end{aligned} \tag{4}$$

where, y_0 , θ_0, M_0, and V_0 respectively are vertical displacement, rotation, moment, and shear force of the foundation where x=0. M and P represent external moment and vertical force. U_M and U_p are the locations of the M and P respectively. $F_1(\lambda x)$, $F_2(\lambda x), F_3(\lambda x), F_4(\lambda x)$ are the shape functions given as follows.

$$\begin{aligned}F_1(\lambda x) &= \cosh\lambda x\cos\lambda x\\ F_2(\lambda x) &= \frac{1}{2}(\cosh\lambda x\sin\lambda x + \sinh\lambda x\cos\lambda x)\\ F_3(\lambda x) &= \frac{1}{2}\sinh\lambda x\sin\lambda x\\ F_4(\lambda x) &= \frac{1}{4}(\cosh\lambda x\sin\lambda x - \sinh\lambda x\cos\lambda x)\end{aligned} \tag{5}$$

2.2. Design of continuous foundations

The design of continuous foundations consists of two stages: preliminary design, and final design. In the preliminary design, the foundation width (b) is determined as follows:

$$b \geq \frac{\sum P}{L \,.\, q_t} \tag{6}$$

where, L is the length of the foundation, q_t is bearing soil stress. After the determination of the foundation, soil-bearing control is performed as follows:

$$q_{t,net} = q_t - 1.4 * 18 \cdot \mathrm{b} \rightarrow q_{t,net} \geq q_o \tag{7}$$

Here, $q_{t,net}$ is nominal soil stress, h is the height of the foundation, and q_o is the stress that occurred in the soil (see Section 2.1 for the computation). If $q_{t,net} < q_o$, b should be increased.

After the ground soil bearing control is achieved, the final design phase is started. the final design phase, the first critical shear force (V_{cr}) is performed as follows:

$$V_{cr} = 0.65. f_{ctd} \,. b. d \;\; \rightarrow V_{cr} \; > V_d \; ; d = h - d' \tag{8}$$

where, f_{ctd} represents the characteristic tensile strength of concrete and d' represents the concrete cover. V_d is the design shear force (the value of the maximum shear force at a distance d from the column face) value.

Required stirrup reinforcement area (A_s) and stirrup spacing (s) are calculated according to the following equation.

$$A_s/s = (V_d - 0.8V_{cr} \,)\left(f_{ywd} \; d\right) \geq A_{smin}/s \tag{9}$$

Here, A_{smin}/s is the minimum required stirrup reinforcement calculated as follows.

$$A_{smin}/s = 0{,}3. b_w. f_{ctd}/f_{ywd} \tag{10}$$

In Equation (10), b_w is the foundation's upper width, f_{ywd} is the yield stress of the stirrup reinforcement.

The longitudinal reinforcement area (A_l) is calculated according to the equation as follows:

$$A_l = \frac{0.85 * b * a}{f_{yd}} \geq A_{lmin}; a = d - \sqrt{d^2 - \frac{2|M_d|}{0.85 f_{cd} b}} \tag{11}$$

where, M_d is the design moment force (see Section 2.1 for the calculation), f_{yd} is the yield design stress of the longitudinal reinforcement, a is the neutral axis length. A_{lmin} is the minimum required longitudinal reinforcement area calculated as follows.

$$A_{lmin} = 0.8 \frac{f_{ctd}}{f_{yd}} * b_w * d \tag{12}$$

According to A_l and A_s/s, reinforcement amounts and diameters are computed.

2.3. Optimization problem of the RC foundation

The study aims to find the most suitable foundation cross-section parameters and reinforcement details in a way that minimizes the foundation cost. For this purpose, the optimization problem of the study is presented mathematically as follows.

Find the optimum design variable vector $\vec{\boldsymbol{x}} = [\boldsymbol{b}, \mathbf{h}, \boldsymbol{\phi}_\mathrm{l}, \boldsymbol{\phi}_\mathrm{s}, \boldsymbol{n}_\mathrm{l}, \boldsymbol{n}_\mathrm{s}]$ to minimize the foundation cost:

$$\text{Min. cost}(\vec{\boldsymbol{x}}) = U_C\, V_C + U_S\, W_S \tag{13}$$

Subject to;

$$g_1(x) = \frac{q_o}{q_{t,net}} - 1 \leq 0 \tag{14}$$

$$g_2(x) = \frac{V_d}{V_{cr}} - 1 \leq 0 \tag{15}$$

$$g_3(x) = \frac{V_d}{V_{max}} - 1 \leq 0 \tag{16}$$

In Equation (13), U_C and U_S respectively are the unit costs of concrete and steel materials. V_C is the volume of the concrete in the foundation. W_S is the total steel weight of the foundation. ϕ_l and ϕ_s represent diameters of longitudinal and stirrup reinforcements. n_l and n_s are the total number of longitudinal and stirrup reinforcement bars. In Equation (16), V_{max} is the maximum shear force occurred in the foundation.

2.4. Optimization method: ABC

Artificial Bee Colony Optimization, developed by Karaboğa [56], was inspired by the foraging behavior of honey bees. In the method, bees are divided into 3 groups according to their duties: employed, onlooker, and scout. Employed bees are responsible for collecting food and sharing food information with the colony. Onlooker bees collect like employed bees, but they select the food source based on the information received from the worker bees. Scout bees are responsible for finding new food sources to replace depleted food sources.

In this method, bees visit a food source during each flight. The food sources chosen by the worker bees should be different from each other. Therefore, the total number of employed bees and the number of food sources are equal. Although onlooker bees do not have to choose different food sources, the total number of flights is equal to the number of food sources. Therefore, the colony size of ABC is equal to the food source. The quality of the food source is inversely proportional to the objective function value. In the method, the food source, the location of the food source, the quality of the food source, the flight of bees to the food source, and the research of the food source represent the foundation design, design variable vector of the design, performance (better objective function value) of the design, change of the design and creation of the design, respectively. The food source is considered used if its performance does not improve when the food source is changed. If the use of the food source exceeds the limit value, the food source is considered exhausted and is deleted from the algorithm. The steps of the ABC algorithm can be detailed as follows [57].

Step 1: The ABC generates initial foundation designs randomly as follows:

$$\mathbf{X}_{i,j} = lb_j + \left(ub_j - lb_j\right) \cdot r \; ; i = 1.2, \dots N_{fs}; j = 1.2, \dots, n \tag{17}$$

Here, **X** is the matrix containing all foundation designs, ub_j and lb_j respectively are the upper and lower boundaries of the j^{th} design variable, r is the pseudo-random number generated in the interval (0,1), N_{fs} is the number of food sources, and n is the dimension of the optimization problem. Initial foundation designs are evaluated according to Section 2.3 and their costs are saved in the algorithm memory.

Step 2: Employed bees modify their foundation designs as follows:

$$\mathbf{X}_{i,j}^{new} = \mathbf{X}_{i,j} + \left(\mathbf{X}_{i,j} - \mathbf{X}_{k,j}\right) \cdot (r - 0.5) \cdot 2 \; ; i = 1.2, \dots N_{fs}; j = 1.2, \dots, n \tag{18}$$

Subscript k represents the neighbor solution (determined randomly) of the i^{th} solution. Then the ABC calculated the modified foundation designs' costs and compares them with their old ones. If new designs have lower costs, new designs replace old ones. Otherwise, old designs remain in the algorithm memory. This procedure is called "Greedy selection"

Step 3: The ABC computes selection rates of the foundation designs in the memory as follows:

$$R_i = 1 - 0.9 \frac{ost_{\ i}}{ost_{\ max}} ; i = 1.2, \dots N_{fs} \tag{19}$$

Subscript max is the index of the foundation design having the highest cost value in the memory. Onlooker bees select designs based on their selection probabilities and modify them using Equation (18). Then ABC uses the Greedy Selection operator.

Step 4: Scout bees check all designs whether they are exhausted or not. If any design is exhausted, the ABC removes it from the memory and the scout bee finds a new solution for the removed ones using Equation (17).

The ABC repeats steps 2-4 until it reaches the maximum design evaluation (iteration) number. ($iter_{max}$). Search parameters of the ABC for this study are available in Table 1.

Table 1. Search parameters of the ABC for this study

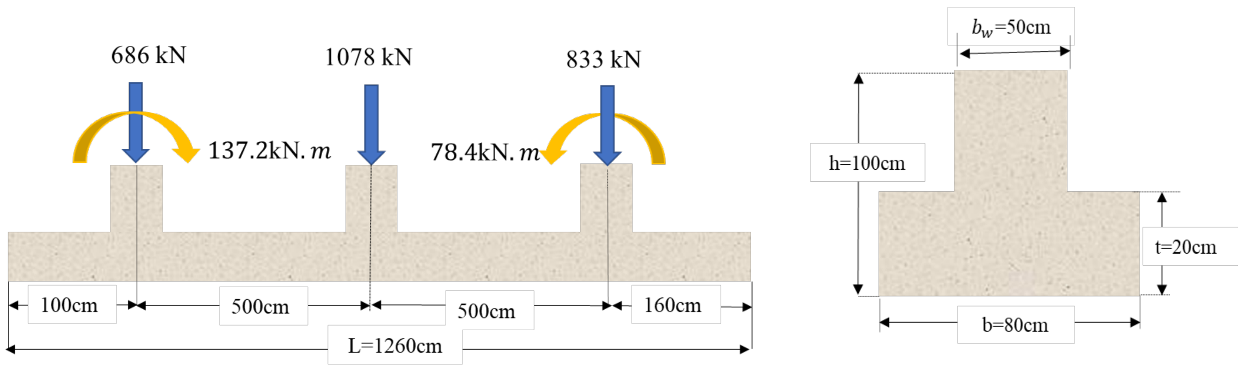
Search Parameter	Numeric Value
N_{fs}	20
Food Limit	150
n	5
$iter_{max}$	10000

3. Design Example

In the study, two design examples are used to test performance of the optimization algorithm and effect of elastic soil behaviour.

3.1. Design example 1

A continuous foundation with a length of 12.6 meters used in the literature(not optimized) is chosen for the current study [76]. Foundation dimensions, loading conditions and are given in Figure 2. This continuous foundation is optimized for both rigid and elastic soil behavior cases.



a) Front view b) Cross-section view

Fig. 2. Design example views

Although the concrete class is taken as C16 in the referenced example, the concrete class is selected as C25 to comply with earthquake standards [77]. S420 is selected as the steel class. Since the soil is semi-hard clay, the bearing coefficient is taken as $K_0 = 14700\ kN/m^3$, the allowable soil stress is 294 kN /m^2, and the columns are 30x40 (40 cm in the direction of the foundation axis). Unit concrete and reinforcement prices respectively are taken as 37.5\$/m^3, 2.19\$/kg. Upper and lower boundaries of cross-section parameters are defined as follows: width b=0.7-2m, height h=0.5-1.5m, and thickness t=0.2-0.6m.

Internal force-stress diagrams of the optimum foundation design for rigid and elastic cases are given in Figure 3. According to these figures, in the rigid case, the soil stress is constant along the foundation base which is equal to 245.25 kN/m^2. However, in the elastic case, the soil stress distribution is parabolic low stresses occurred at the edges and high stresses occurred in the middle of the foundation. In the moment diagram of the rigid design, higher moment values take place in both span and column connection regions. Shear force distributions of elastic and rigid designs are very close to each other.

The optimum cost and design details are given in Table 2. According to Table 2, the lowest optimum cost value was obtained in the elastic design condition (\$1275.12). This cost is 6.9% lower than the optimum cost for the rigid case. When the elastic solution is compared to the reference result, the cost of the elastic solution is 32.27% less than the cost of the reference solution. Stirrups spacing details of all solution areas same which equals minimum requirements. Width is used at the same value in rigid and elastic solutions. However, the height value is less in the elastic design. Since the height value is lower in the elastic design, it contributed to the reduction of the concrete and reinforcement costs.

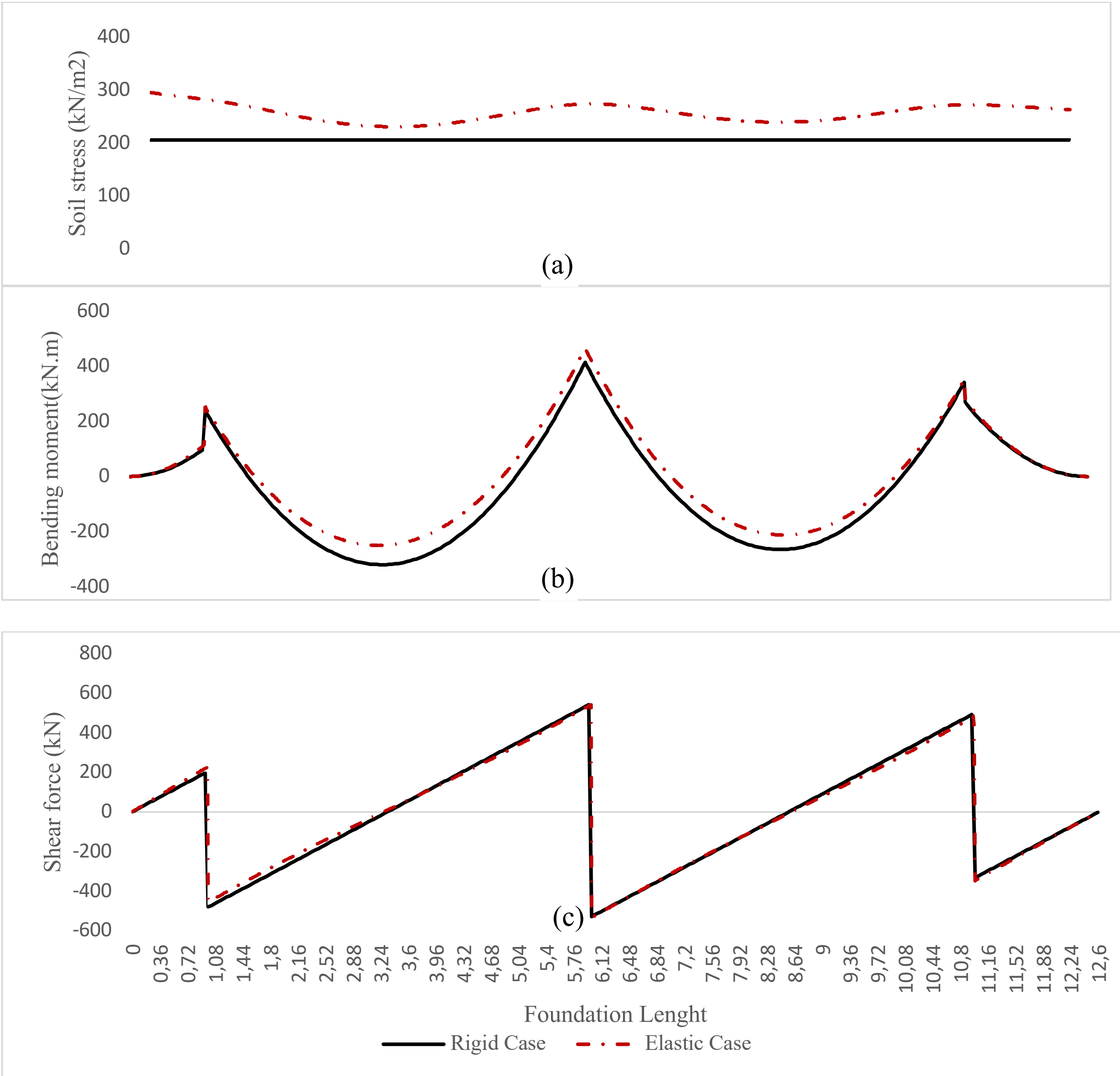


Fig. 3. Internal action diagrams of the optimum foundation design for rigid and elastic case (a): Soil stress, (b): Moment diagram, (c): Shear force diagram. Units

Table 2. Cost and design details of the designs

	Rigid solution	**Elastic solution**	**Ref. solution**
With	75cm	75cm	80 cm
Height	65cm	55cm	100 cm
Thickness	30 cm	30cm	20 cm
Stirrups spacing (mid-zone)	20cm	20cm	20 cm
Stirrups spacing (sup- zone)	15cm	15cm	15 cm
Stirrup reinforcement	ϕ10	ϕ10	ϕ10
Tension long. reinf.	4ϕ20+4ϕ22	4ϕ18	4ϕ20
Comp. long. reinf.	4ϕ14+2ϕ14i+4ϕ20+4ϕ16i	3ϕ18+ 3ϕ16i+7ϕ22i	4ϕ16+12ϕ14i
Web reinforcement	2ϕ14	-	4ϕ14
Dist.-bar reinforcement	ϕ12	ϕ12	ϕ12
	ϕ10	ϕ10	ϕ10
Total cost ($)	1363.94 USD	1275.12 USD	1686.66 USD

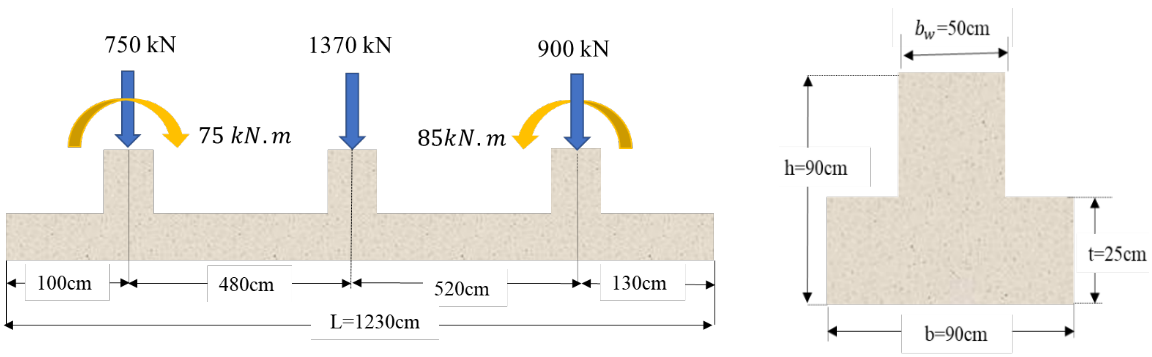
Limit constraint ratios (Soil bearing, shear, bending, and stirrup) of the foundation design are given in Table 3. In table 3, for all solutions, the soil-bearing load capacity ratios exceed 95%. For optimum designs (both for elastic and rigid cases), stirrup load capacity ratios are the highest ratios among other constraints. However, in the reference solution, soil-bearing control is the dominant constraint. According to shear Control, the capacities of all solutions are under 40%. If the value is above 1 in stirrup control, the required reinforcement is preferred instead of the minimum reinforcement. The reason why it gives 1.680* and 1.846* values in rigid and elastic solution is due to this situation.

Table 3. Limit constraint values of the designs

	Rigid solution	Elastic solution	Ref. solution
Soil bearing control	0.989	0.980	0.958
Shear Control	0.357	0.393	0.155
Stirrup Control	1.680*	1.846*	0.872

3.2. Design example 2

A continuous foundation with a length of 12.3 meters used in the literature (not optimized) is chosen for the current study [78]. Foundation dimensions, loading conditions and are given in Figure 4. This continuous foundation is optimized for both rigid and elastic soil behavior cases. Unit concrete price as taken as is 39.5$/m^3.



a) Front view b) Cross-section view

Fig. 4. Design example views

In the reference example, the concrete and steel grades was chosen as C30 and S240 respectively [78]. Soil type is considered as the ground semi-hard clay and the bearing coefficient value of the soil is $K_0 = 14700$ kN/m^3. The bearing soil stress is taken as 300 kN/m^2 and the columns are 30x50 (50 cm in the direction of the foundation axis). Unit reinforcement price, cross section parameters are shown in the previous example.

Internal force-stress diagrams of the optimum foundation design for rigid and elastic cases are given in Figure 5. According to the figure, in the rigid case, the soil stress is constant along the foundation base which is equal to 273 kN/m^2. However, in the elastic case, the soil stress distribution is parabolic low stresses occurred at the edges and high stresses occurred in the middle of the foundation. In the moment diagram of the rigid design, higher moment values take place in both span and column connection regions. Shear force distributions of elastic and rigid designs are very close to each other.

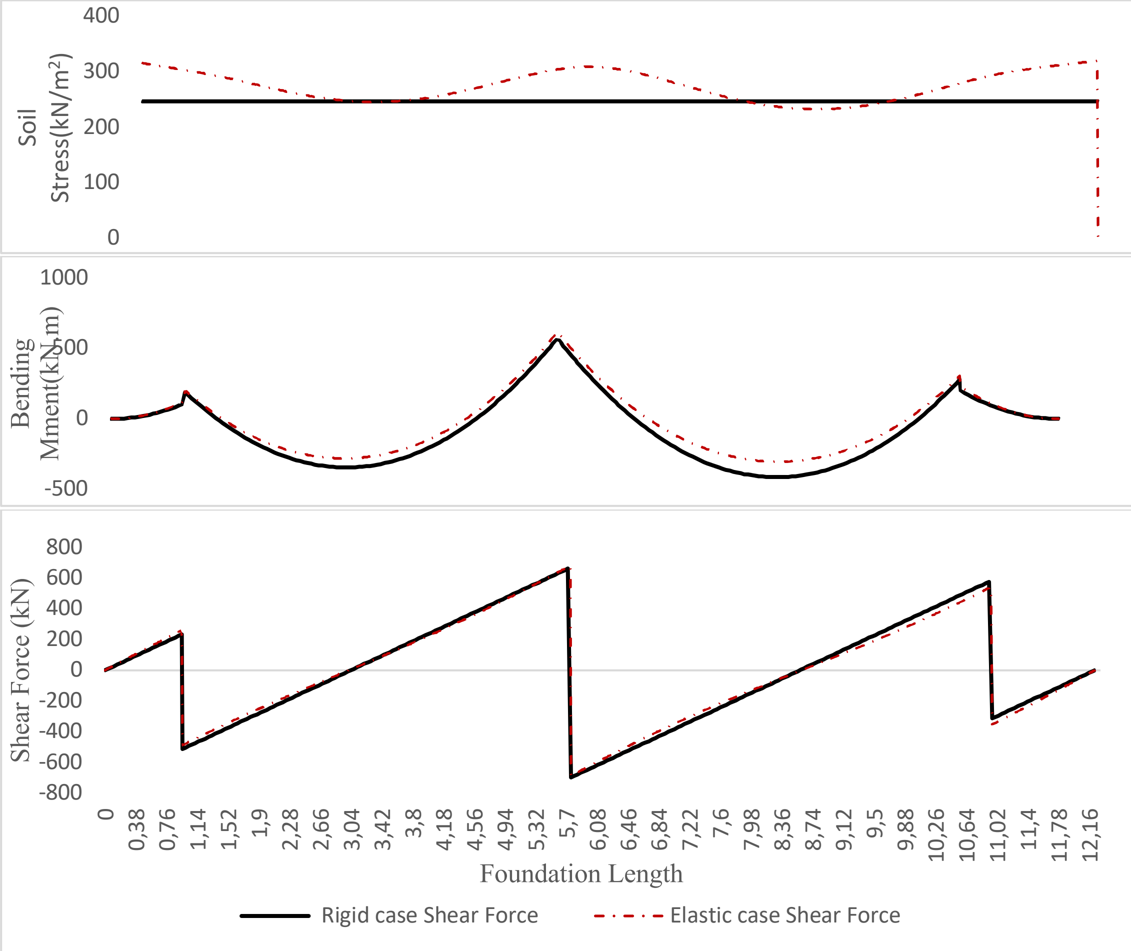


Fig. 5. Internal action diagrams of the optimum foundation design for rigid and elastic case (a): Soil stress, (b): Moment diagram, (c) shear force diagram. Units

The optimum cost and design details are given in Table 4. According to Table 4, the lowest optimum cost value was obtained in the elastic design condition ($1530.75). This cost is 5.2% and 11.48% lower than the optimum cost for the rigid case and reference solution respectively. Stirrups spacing details of all solution areas same which equals minimum requirements. Width is used at the same value in rigid and elastic solutions. Similar to the first example, foundation heights are different and elastic solution has the minimum foundation height. Therefore, in elastic solution the costs of concrete and reinforcement are lower than other solutions.

Table 4. Cost and design details of the designs

	Rigid solution	**Elastic solution**	**Ref. solution**
With	90cm	90cm	90 cm
Height	75cm	70cm	90 cm
Thickness	30 cm	30cm	25 cm
Stirrups spacing (mid-zone)	20cm	20cm	20 cm
Stirrups spacing (sup- zone)	15cm	15cm	15 cm
Stirrup reinforcement	2ϕ10	2ϕ10	2ϕ10
Tension long. reinf.	4ϕ22+4ϕ24	4ϕ18+4ϕ20	4ϕ20+4ϕ22
Comp. long. reinf.	3ϕ18+4ϕ12i+4ϕ22i	4ϕ16+ 1ϕ12i+4ϕ24i+3ϕ14i	4ϕ14+8ϕ14i+4ϕ20i
Web reinforcement	2ϕ16	2ϕ16	4ϕ14
Dist.-bar reinforcement	ϕ12	ϕ12	ϕ12
	ϕ10	ϕ10	ϕ10
Total cost ($)	1611.41 USD	1530.75 USD	1706.55 USD

Limit constraint ratios (Soil bearing, shear and stirrup) of the foundation design are given in Table 5. In table 5, for all solutions, the soil-bearing, stirrup load capacity ratios exceed 98%. For optimum designs (both for elastic and rigid cases), stirrup load capacity ratios are the highest ratios among other constraints. In stirrup control, if the value is above 1, the required reinforcement is preferred instead of the minimum reinforcement. The reason why it gives a value of 1.288* in the reference solution is due to this situation. However, in the reference solution, soil-bearing control is the dominant constraint.

Table 5. Limit constraint values of the designs

	Rigid solution	**Elastic solution**	**Ref. solution**
Soil bearing control	0.976	0.972	0.989
Shear Control	0.317	0.310	0.392
Stirrup Control	1.692	1.657	*1.288

4. Conclusions

In the study, an optimization algorithm has been developed for elastic and rigid continuous foundations. An example used in the literature is optimized for both rigid and elastic analysis with the developed program. In line with the results obtained, the following inferences were made regarding the performance of the current algorithm and the effect of the elastic soil behavior on the optimum foundation design.

In terms of optimum cost, the elastic design outperforms the rigid design. This is because the minimum foundation dimensions and minimum reinforcement quantities relative to the reference solution are sufficient for the foundation to bear the superstructure loads. However, it has been observed that the load capacity ratios of the elastic design are close to the limit value. Especially in the elastic design, 97% of the soil capacity has been reached. In this case, it is estimated that lower costs will be obtained with the elastic design under more difficult loads.

When the optimum results are compared with the literature sample, the optimum results gave lower results than the literature sample results. Therefore, it can be said that the developed algorithm performs well for the existing examples.

Examination of the performance of novel metaheuristic techniques by adding new metaheuristic techniques and optimization with different objective functions such as carbon dioxide emission are considered future studies.

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